First Results from the Pierre Auger Project

A new cosmic ray observatory designed for a high statistics study of the the Highest Energy Cosmic Rays.

Jim Beatty (Ohio State)
for the Pierre Auger Collaboration

Colorado, USA
(in planning)

Mendoza, Argentina
(construction underway)

Outline

- **Description of the Experiment**
  - **Goals**
  - **Operation**
  - **Performance**

- **The Model-Independent Energy Spectrum**
- **Anisotropy results**
- **Photon fraction limit**

The Auger Collaboration

Participating Countries

Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*

***Associate**

63 Institutions,
369 Collaborators

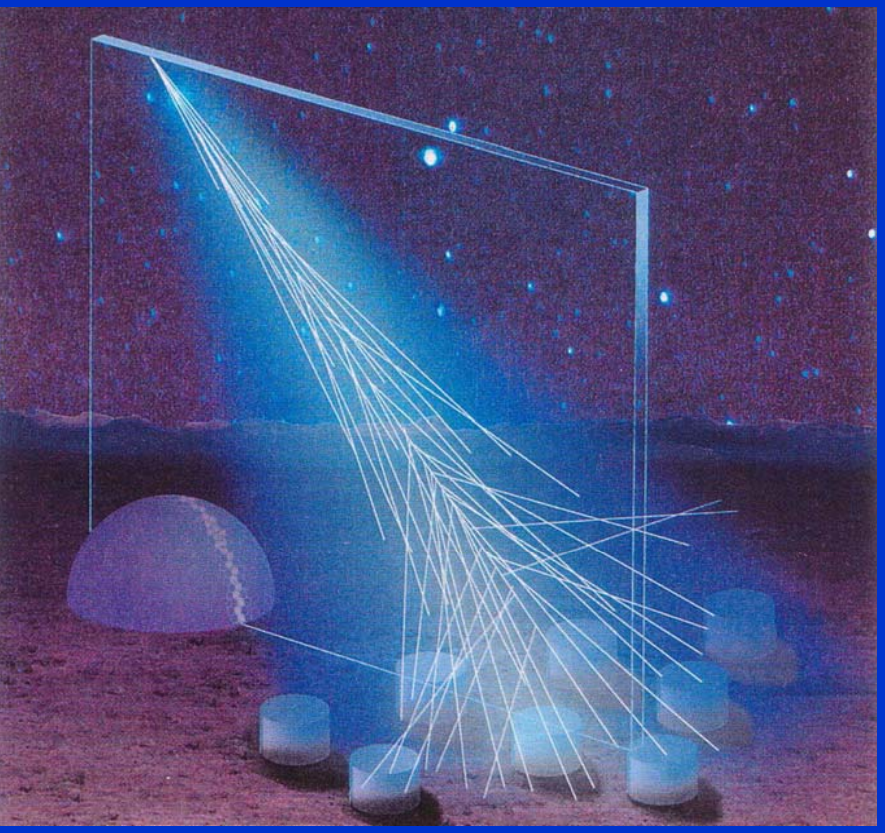
Science Objectives

- **Cosmic ray spectrum above 10^{19} eV (= 10 EeV)**
  - ***Measure the shape of the spectrum in the region of the GZK feature***
    - Spectrum is predicted to be sharply attenuated at E>5 10^{19} eV due to scattering on CMB photons
- **Arrival direction distribution**
  - ***Search for departure from isotropy – point sources***
- **Composition**
  - ***Light or heavy nuclei, photons, exotics?***

Design Features

- **High statistics (aperture >7000 km^2 sr above 10^{19}eV in each hemisphere) → Actual threshold 3 10^{18}eV**
- **Hybrid configuration –surface array with fluorescence detector coverage**
- **Full sky coverage with uniform exposure**

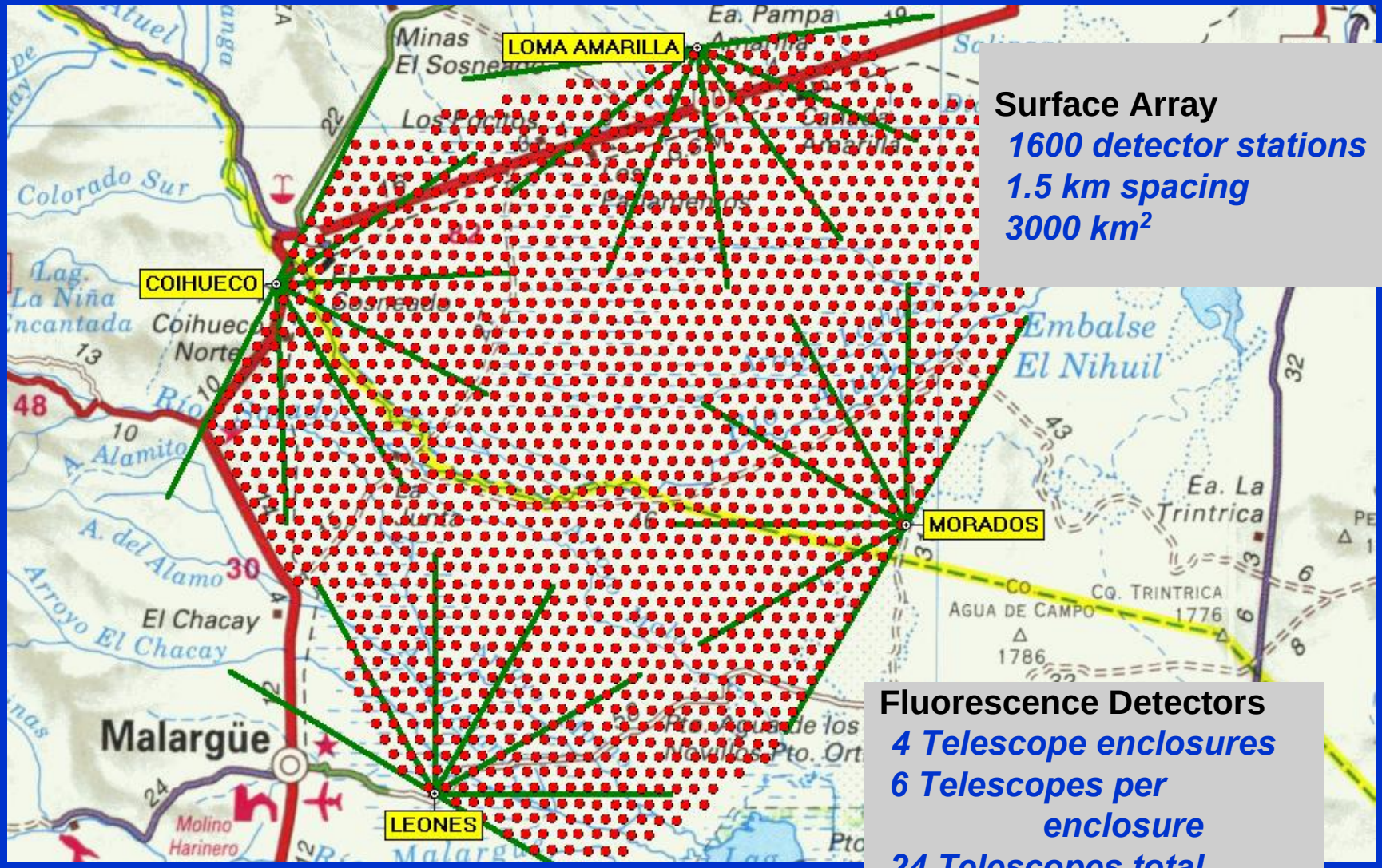
The Hybrid Design



A large surface detector array combined with air fluorescence detectors results in the unique and powerful design

- **Simultaneous shower measurement allows for transfer of the nearly calorimetric energy calibration from the fluorescence detector to the event gathering power of the surface array.**
  - **FD duty cycle ~10%**
  - **SD duty cycle ~100%**
- **Different measurement techniques force understanding of systematic uncertainties in each.**
- **Reconstruction synergy for precise measurements in hybrid events.**
- **A complementary set of mass sensitive shower parameters contributes to the identification of primary composition.**

The Observatory Plan



Surface Array

1600 detector stations

1.5 km spacing

3000 km^2

Fluorescence Detectors

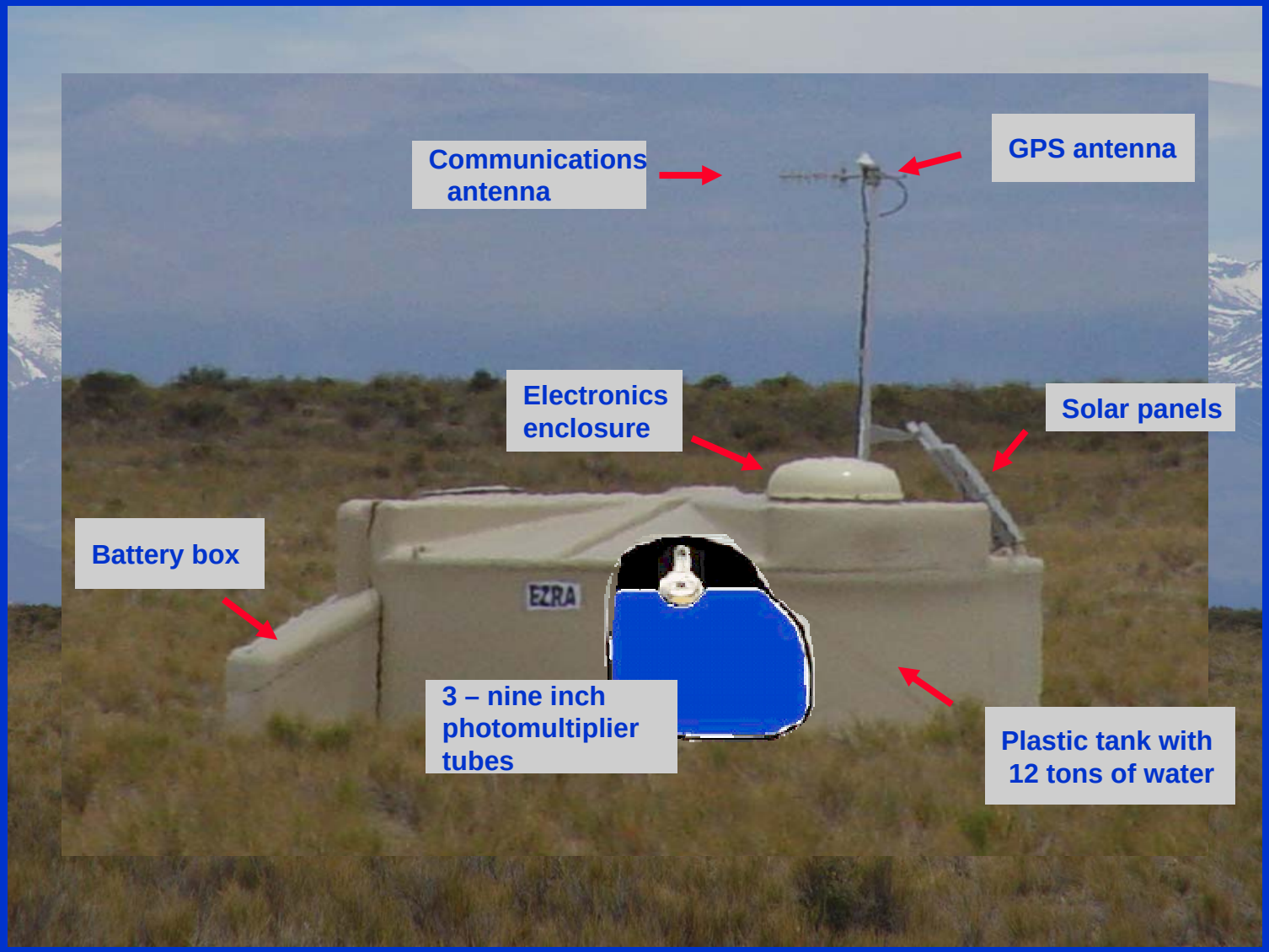
4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

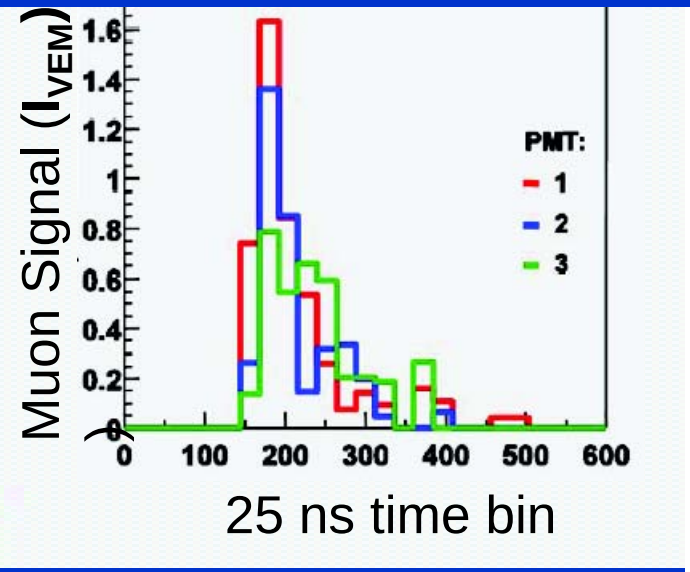
The Surface Array

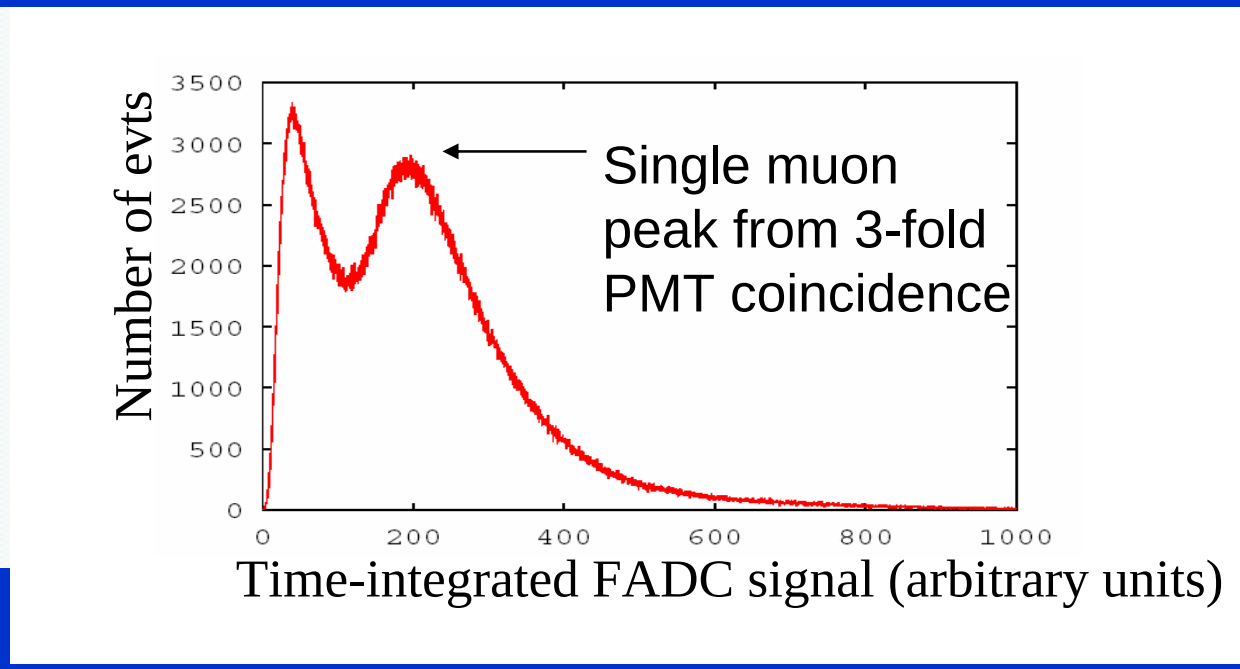
Detector Station



Surface Detector Deployment

SD tanks are self-calibrating (Atmospheric muons used as a standard candle)

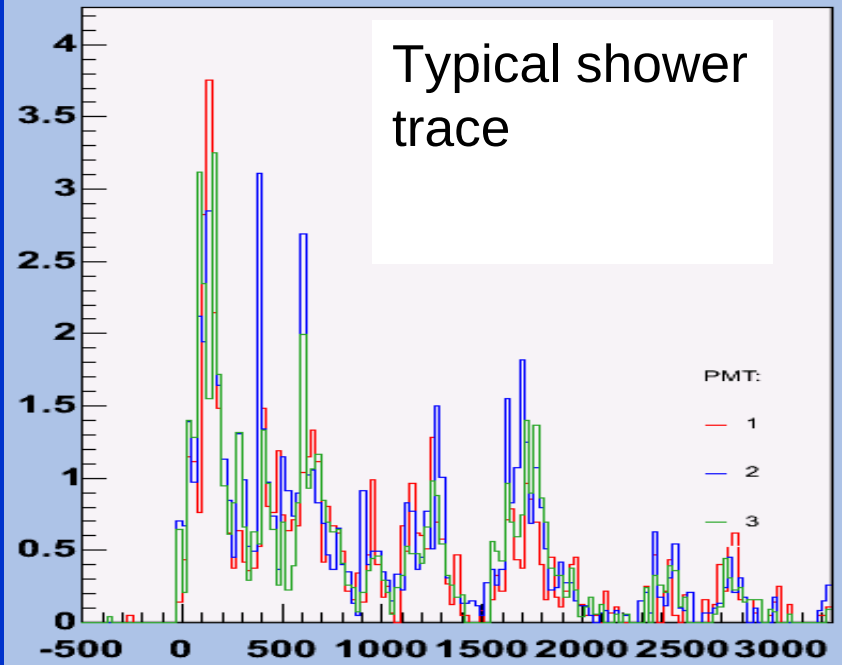


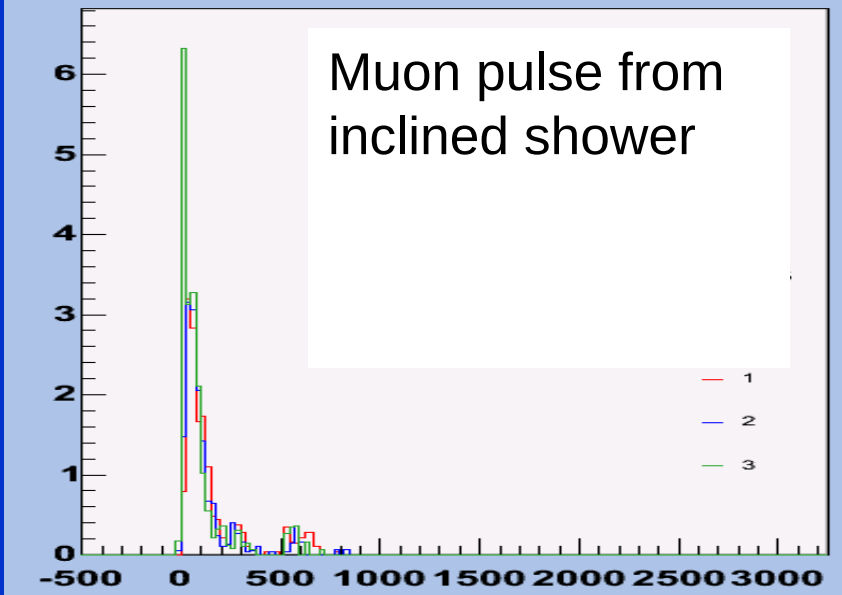


- **Measure all signals in Vertical Equivalent Muon units (VEM).**
- **Trigger thresholds expressed in instantaneous current I_{VEM}**
  - **Dynamic range 0-700 I_{VEM}**
- **Time-integrated signals for energy measurement expressed in Q_{VEM}**

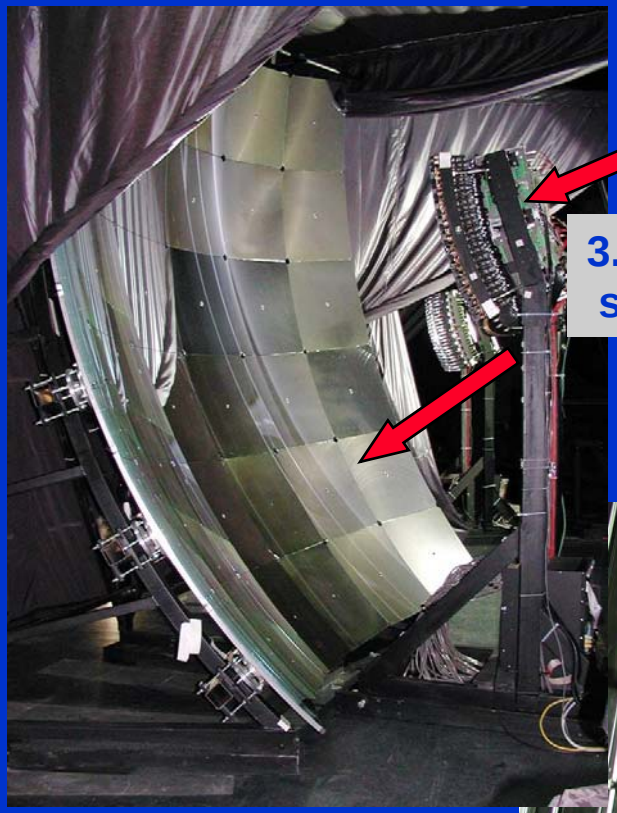
SD triggers

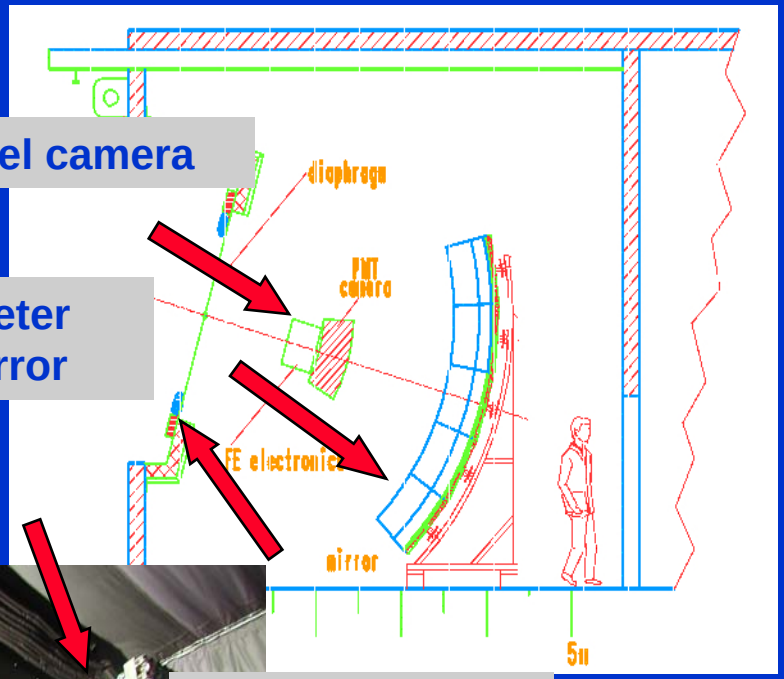
- **Time-over-threshold (TOT) 1-5Hz**
  - **Long signals**
- **Threshold 20Hz**
  - **Fast signals (inclined showers)**
- **Central trigger, rate~3000/day**
  - **look for space-time clusters of triggered tanks**
- **Event selection (for current spectrum analysis)**
  - **look for at least 3 TOT triggers in a compact configuration**
  - **~600/day (~0.9/tank/day)**

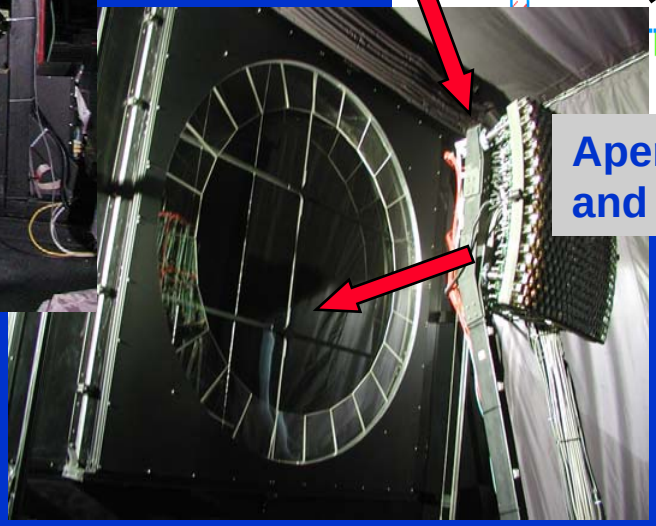




The Fluorescence Detector







440 pixel camera

3.4 meter diameter segmented mirror

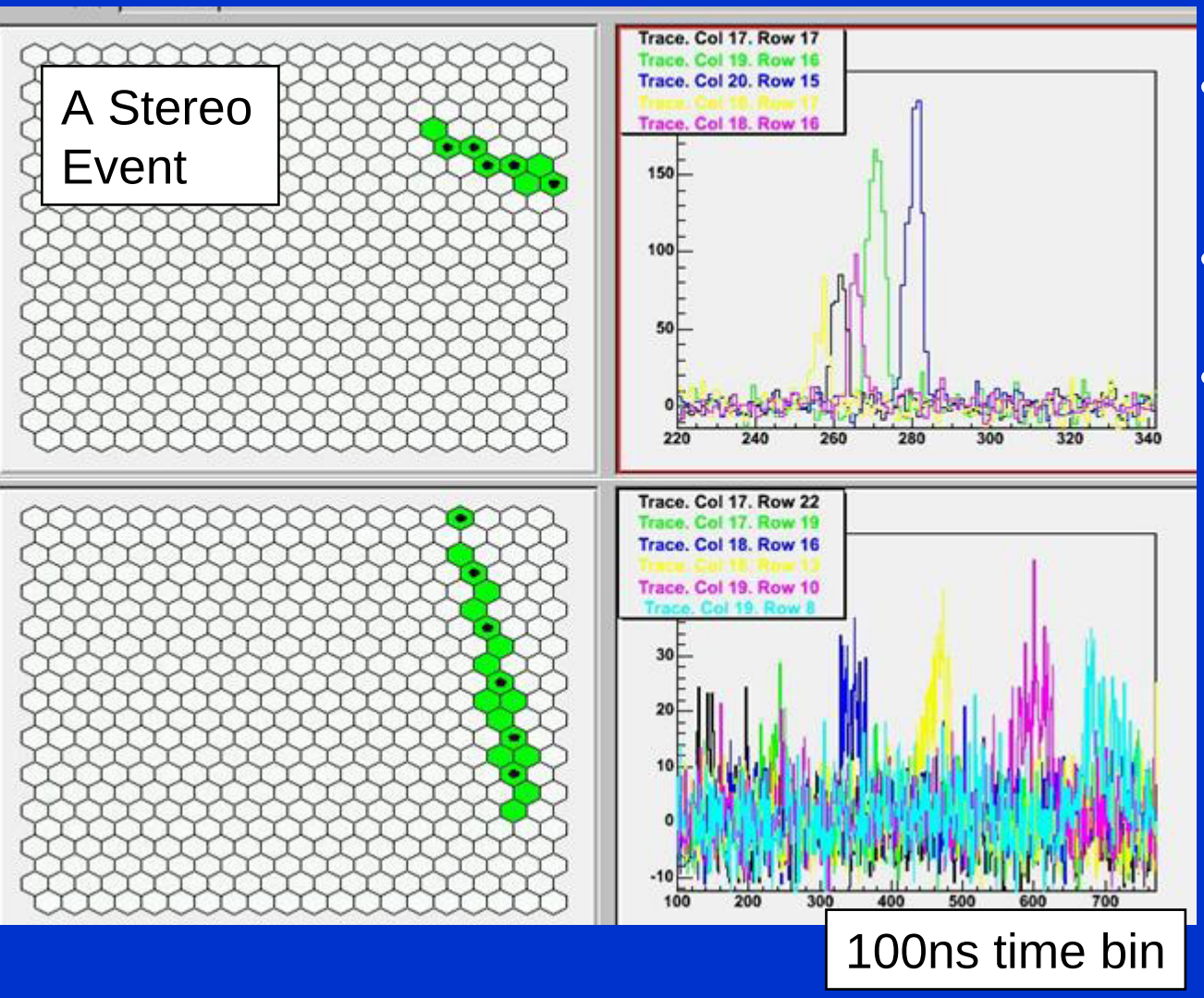
Aperture stop and optical filter

The Fluorescence Detector

Los Leones

30 deg x 30 deg x 30 km field of view per eye

FD Triggers



- **Threshold trigger on individual pixels**
- **Look for "tracks"**
  - **1 Hz trigger rate per 6 cameras**
- **Multi-camera events merged within 2 sec**
- **Geometry recon within 5 sec, and passed to central data acquisition system**
  - **Induces SD readout of tanks within range.**
  - **Obtain "Hybrid" events with both fluorescence longitudinal profile and surface detector signals.**

Atmospheric Monitoring and Fluorescence Detector Calibration

Atmospheric Monitoring

Central Laser Facility (laser optically linked to adjacent surface detector tank)

- **Atmospheric monitoring**
- **Calibration checks**
- **Timing checks**

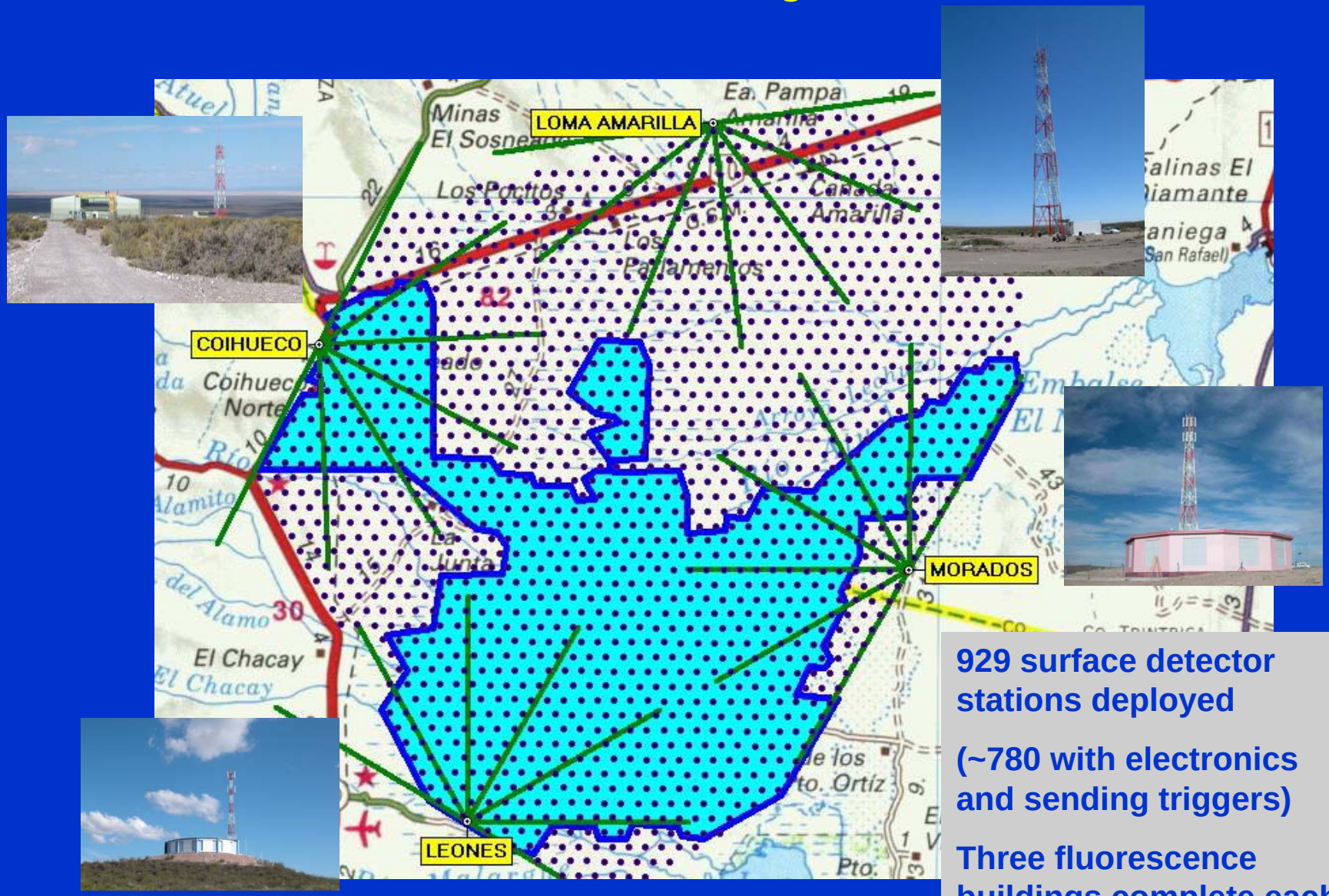
Absolute Calibration

Drum for uniform illumination of each fluorescence camera

Radiosondes for atm profile

Lidar at each fluorescence eye for atmospheric profiling - "shooting the shower"

Construction Progress



929 surface detector stations deployed

(~780 with electronics and sending triggers)

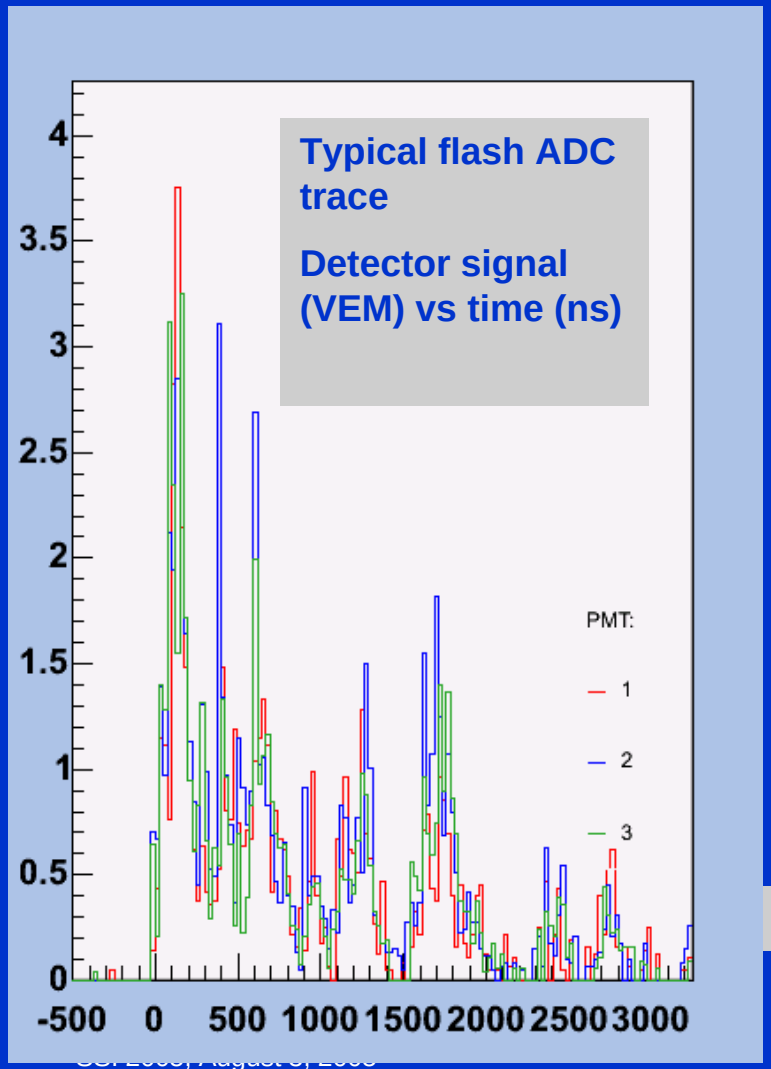
Three fluorescence buildings complete each with 6 telescopes

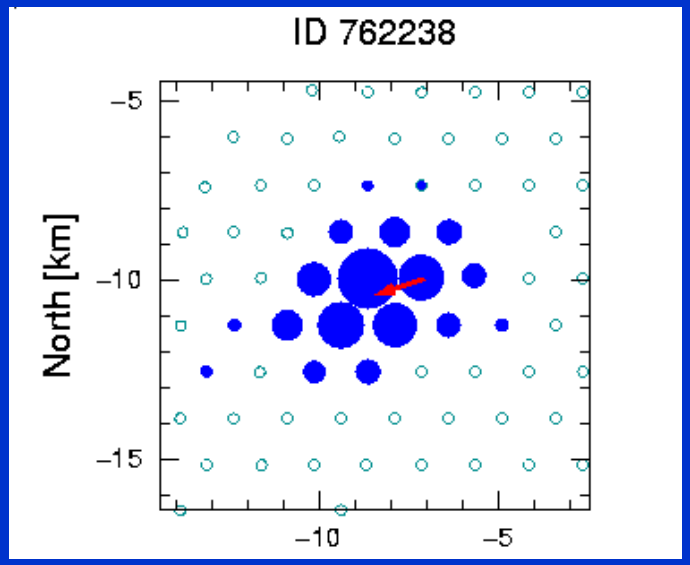
SSI 2005, August 3, 2005

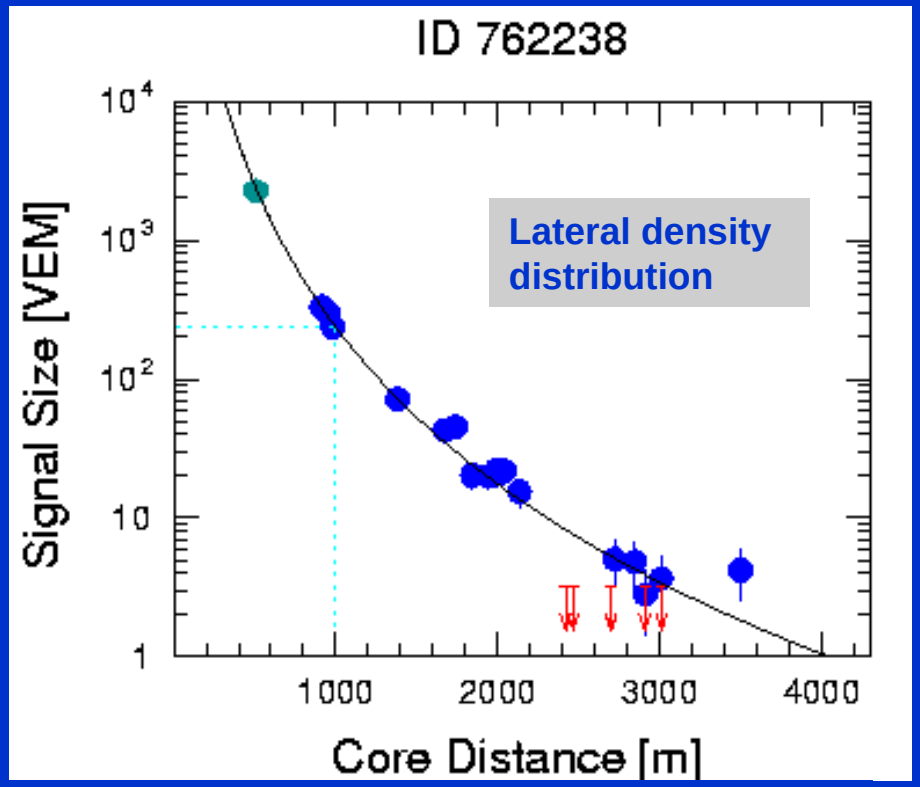
Jim Beatty for the Pierre Auger Collaboration

Example Event 1

A moderate angle event - 762238
Zenith angle ~ 48º, Energy ~ 70 EeV

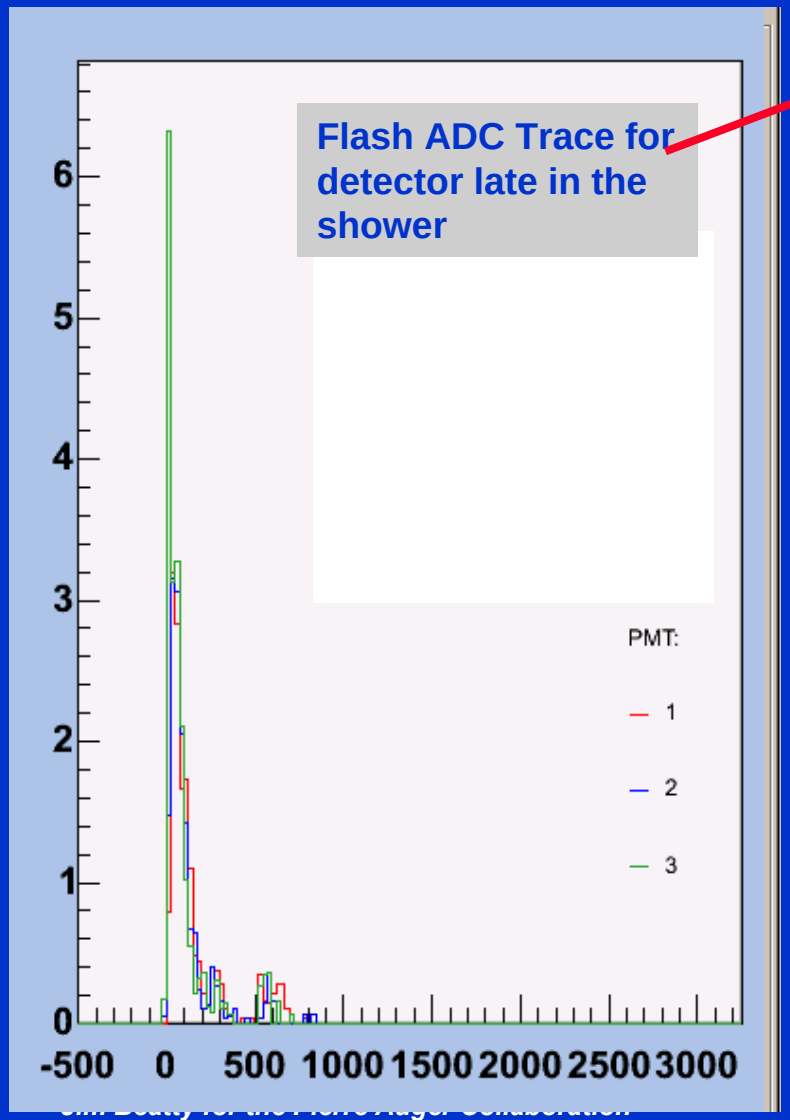


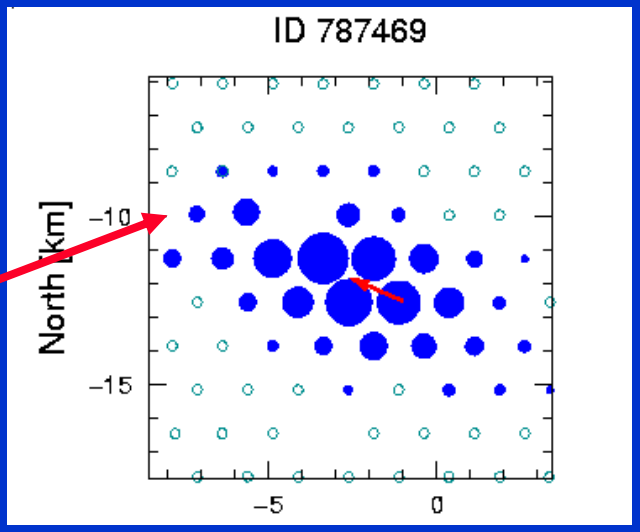


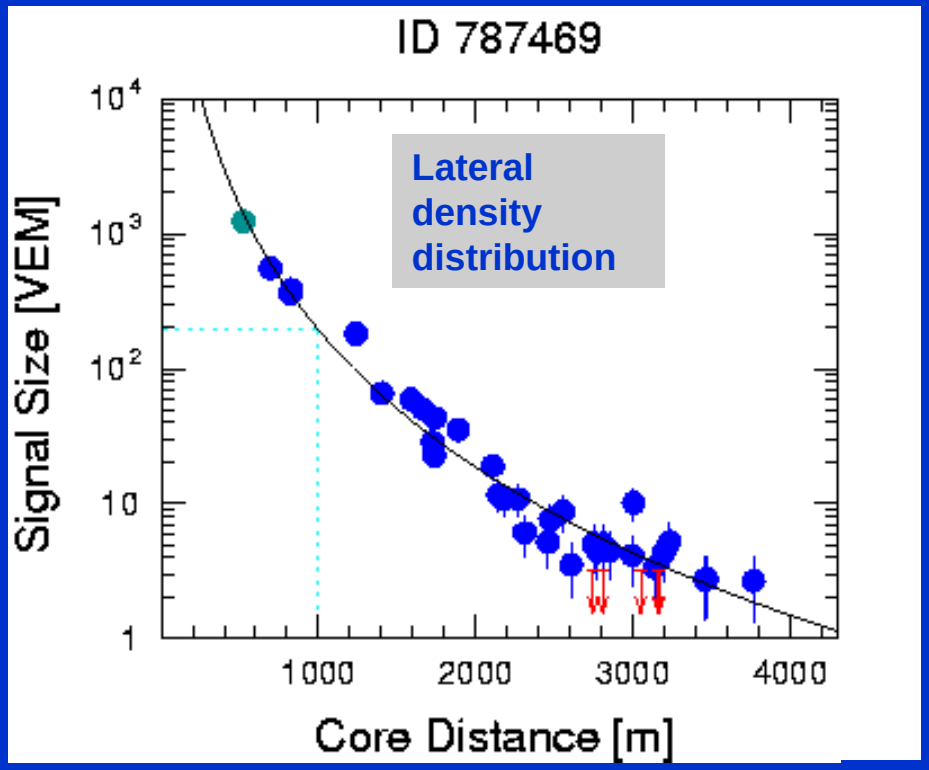


Example Event 2

A high zenith angle event - 787469
Zenith angle ~ 60º, Energy ~ 86 EeV



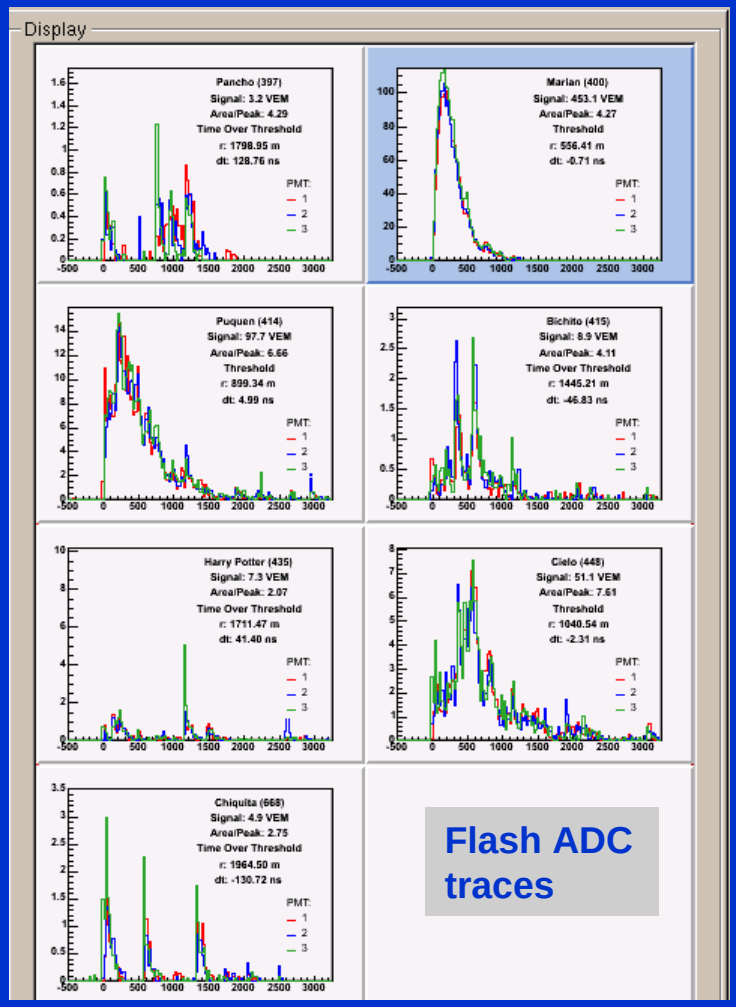


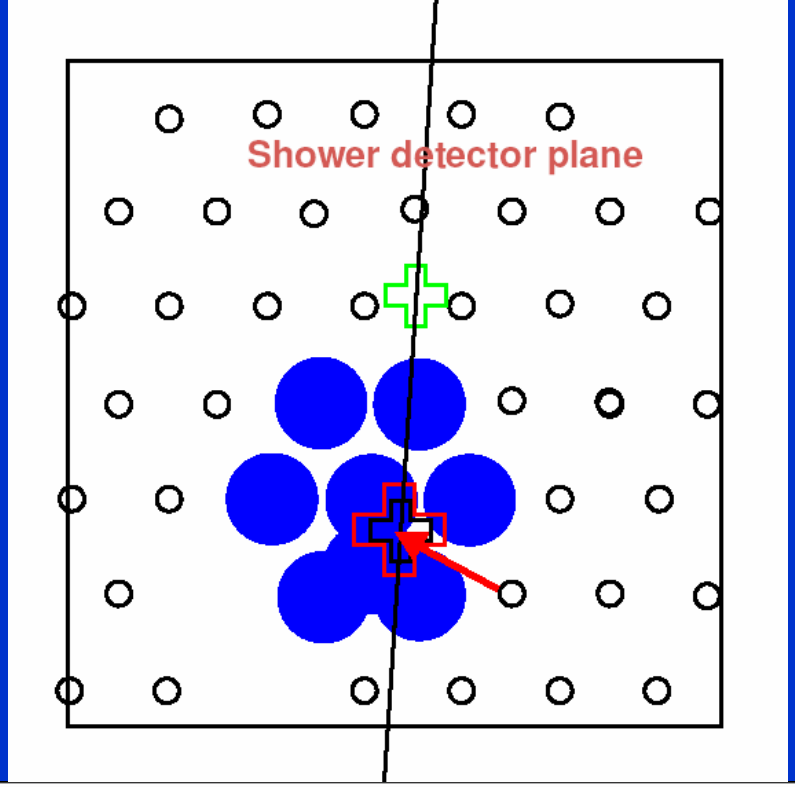


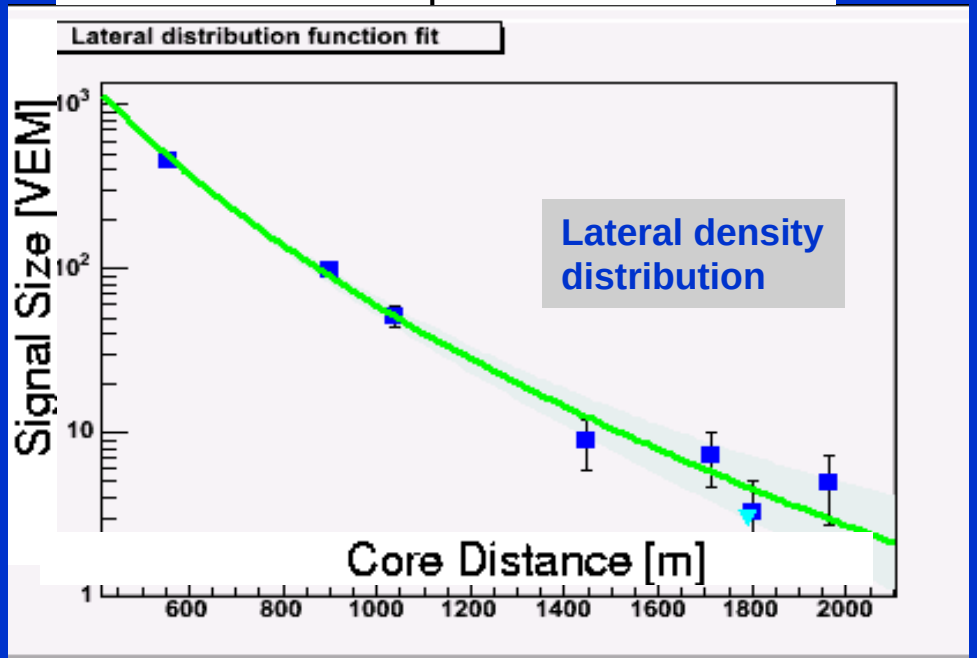
Example Event 3

A hybrid event – 1021302

Zenith angle ~ 30º, Energy ~ 10 EeV







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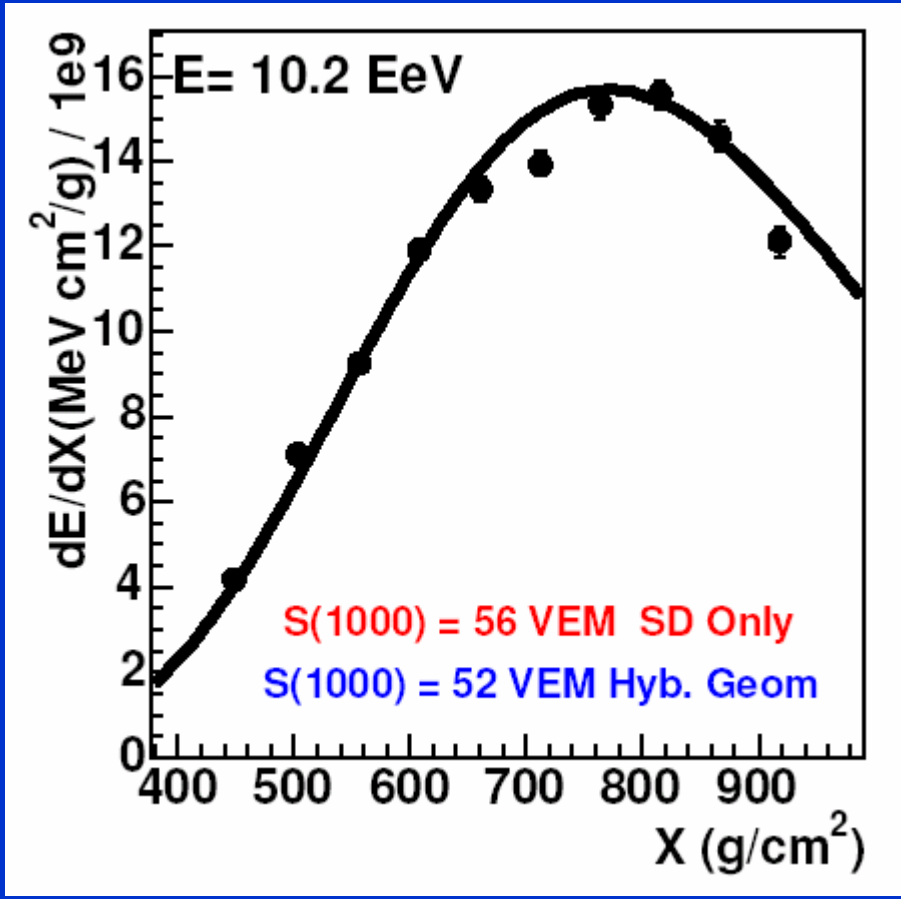
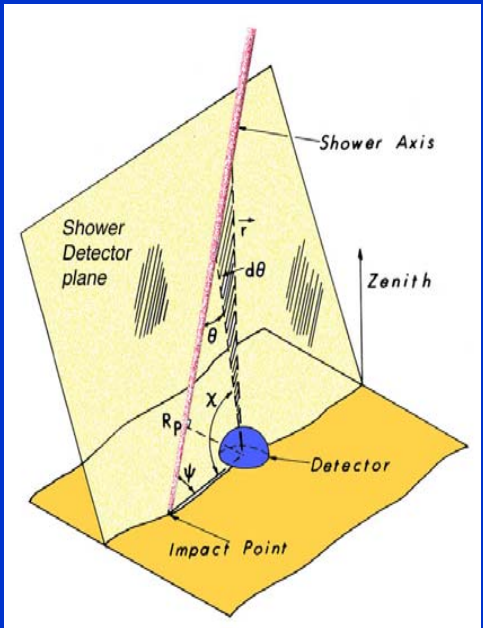
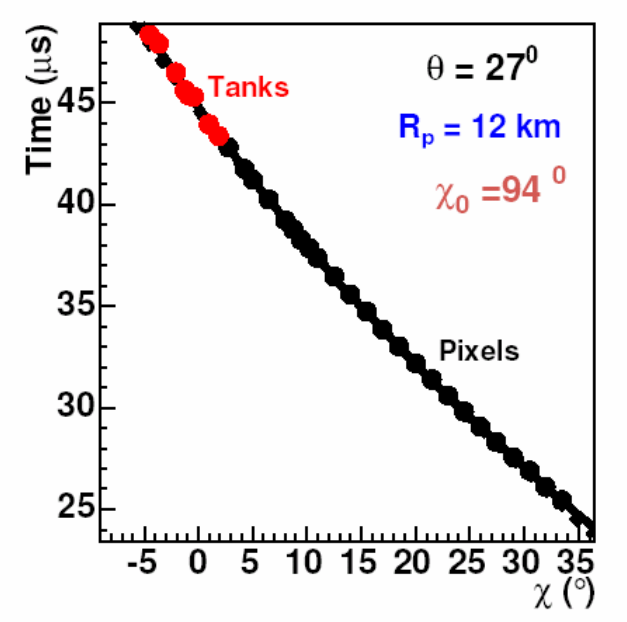
Example Event 3

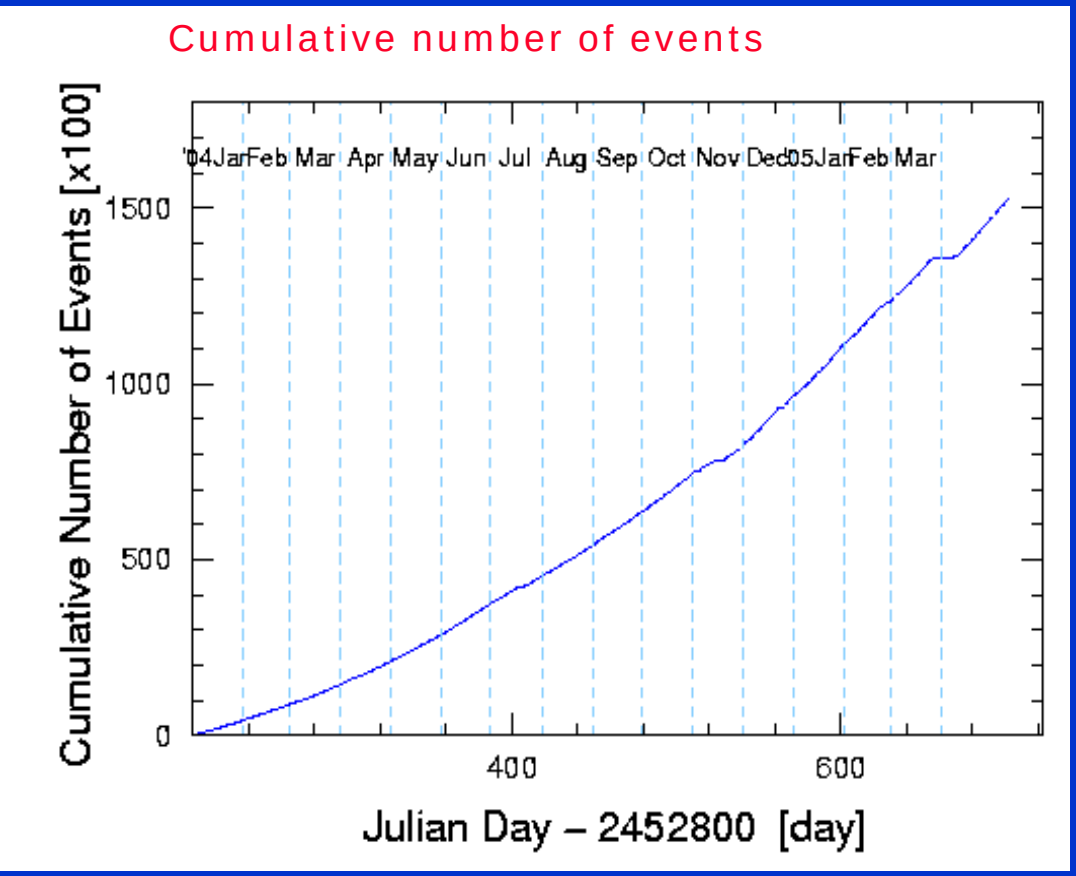
A hybrid event – 1021302
Zenith angle ~ 30º, Energy ~ 10 EeV







The First Data Set



Collection period – 1 Jan 2004 to 5 June 2005

Zenith angles - 0 - 60º

Total acceptance – 1750km² sr yr

(~ 1.07 * AGASA)

Surface array events

(after quality cuts)

Current rate - 18,000 / month

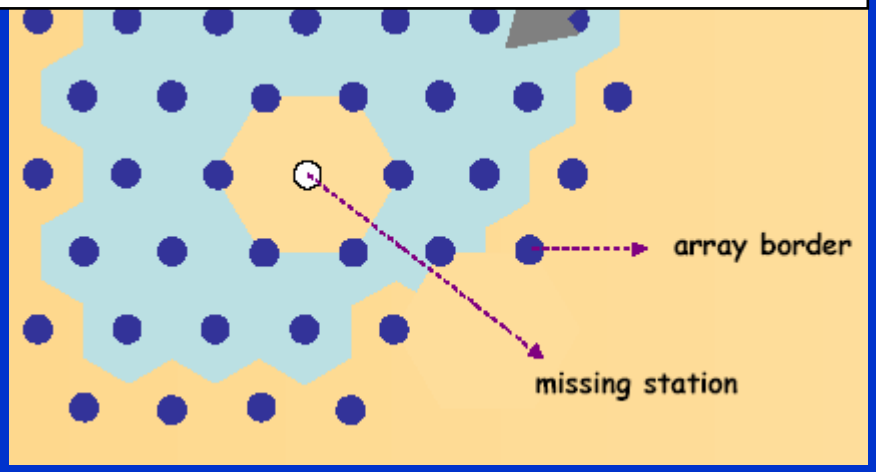
Total - 150,000

The SD Exposure Computation

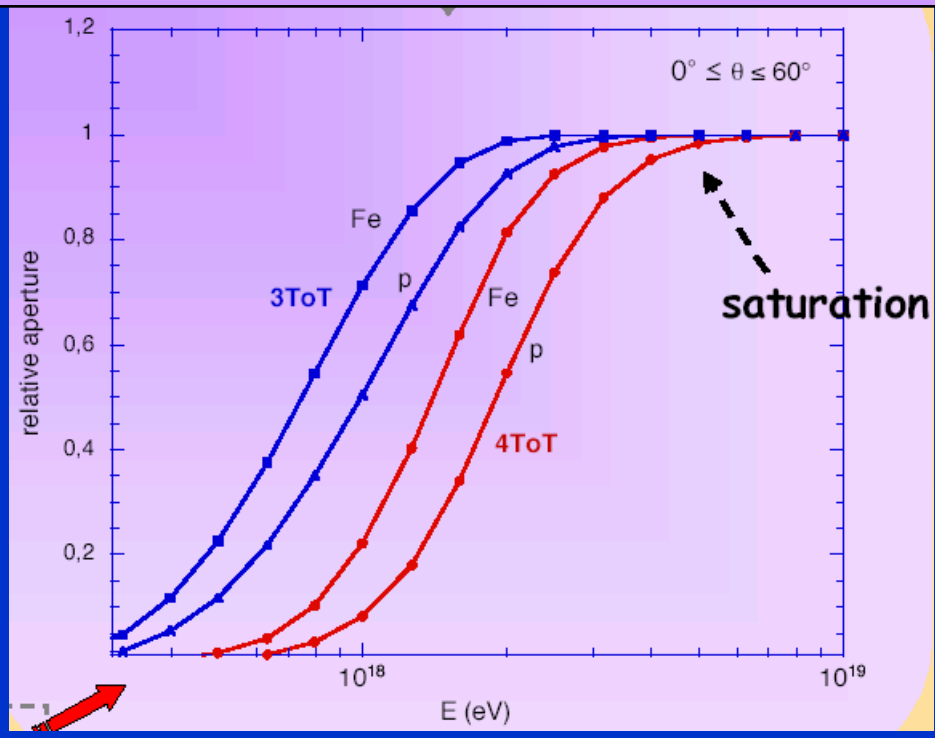
- **Determine the instantaneous effective surface area by monitoring the detector status in real-time.**

Multiply the trigger efficiency by the effective surface area of the array.

Integrate over solid angle and time.

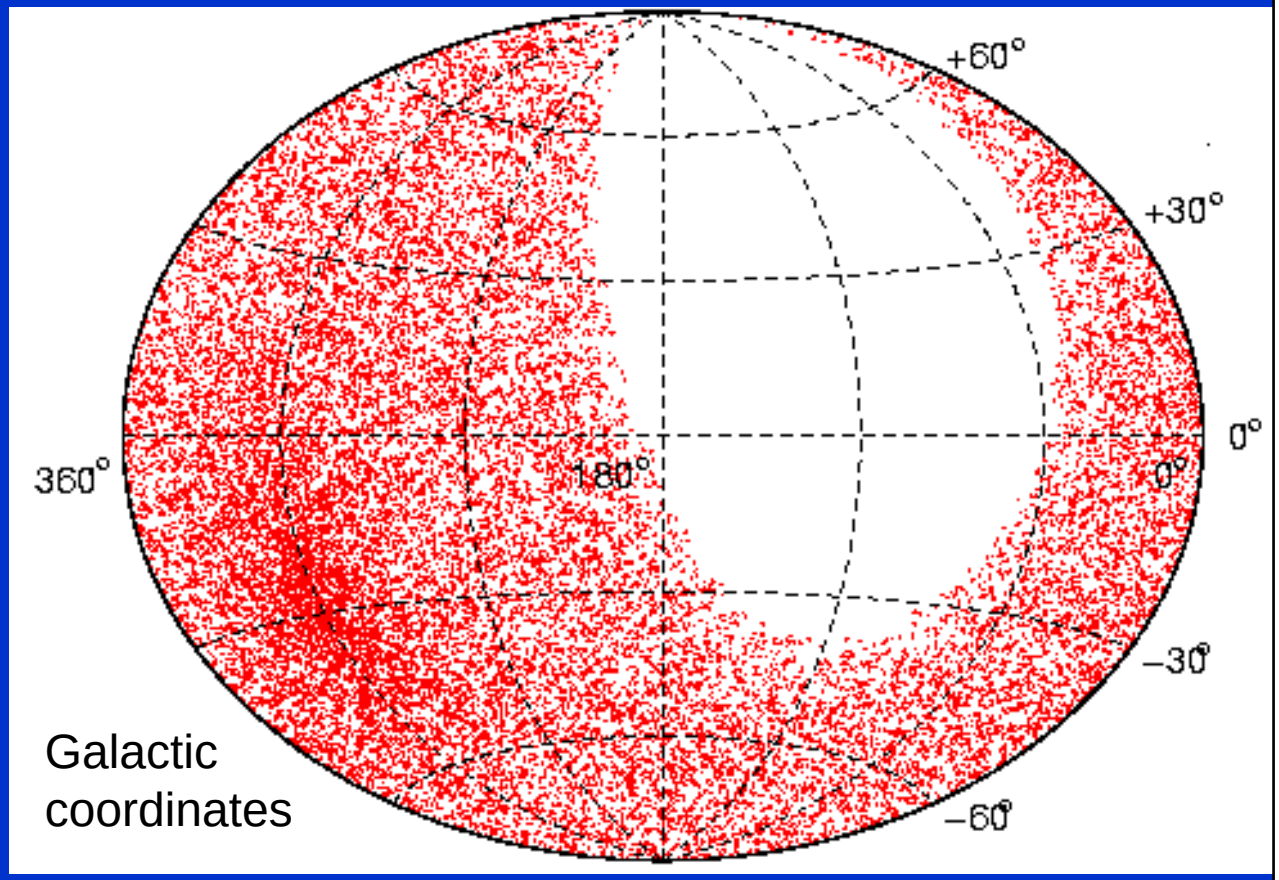


Solid angle-averaged trigger efficiency from simulations



Exposure=1750 km^2 sr yr
= AGASA*1.07

Sky Map of Data set

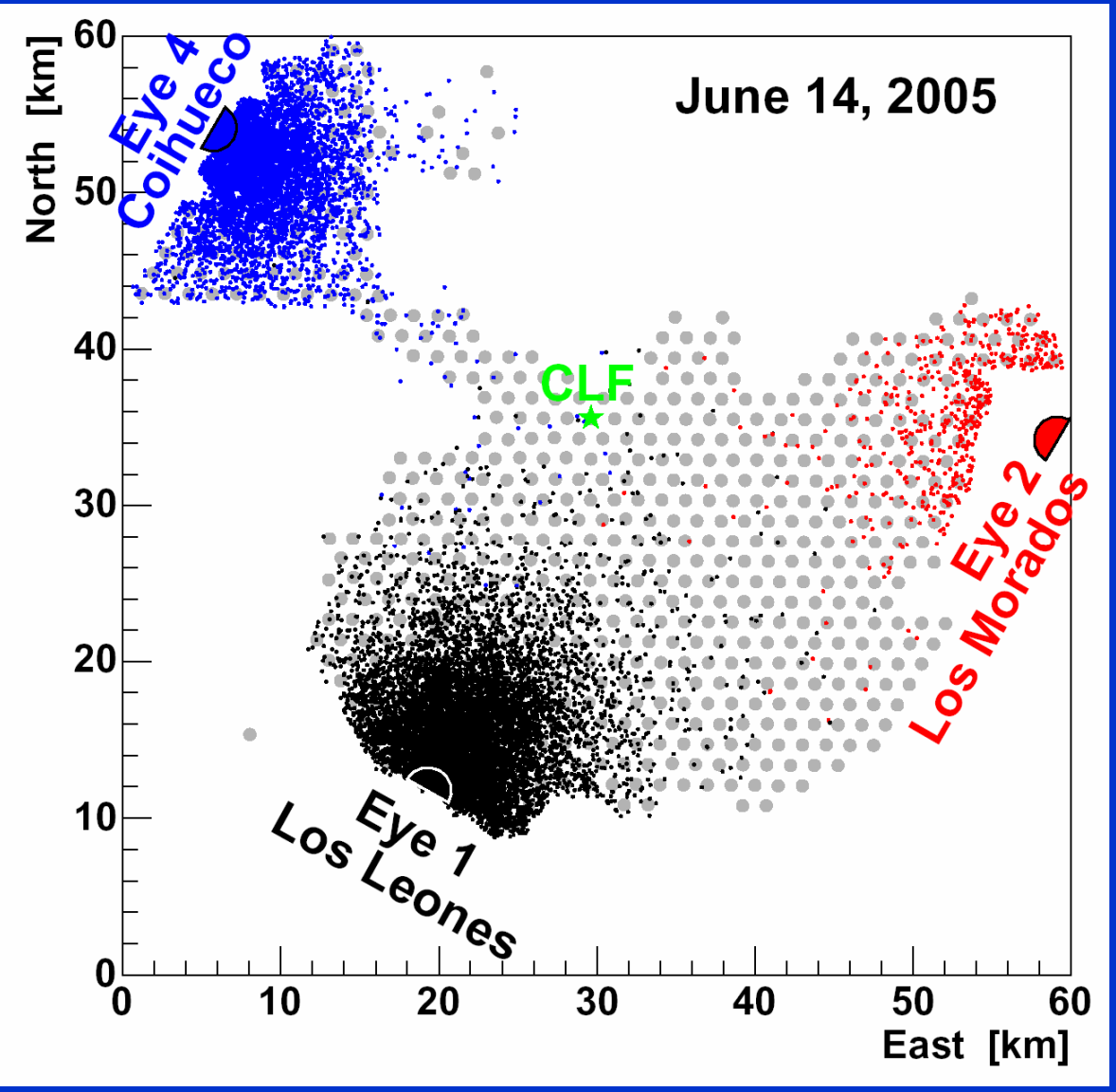


The Auger southern site is at 36° S latitude.

A region near the south celestial pole is always in view.

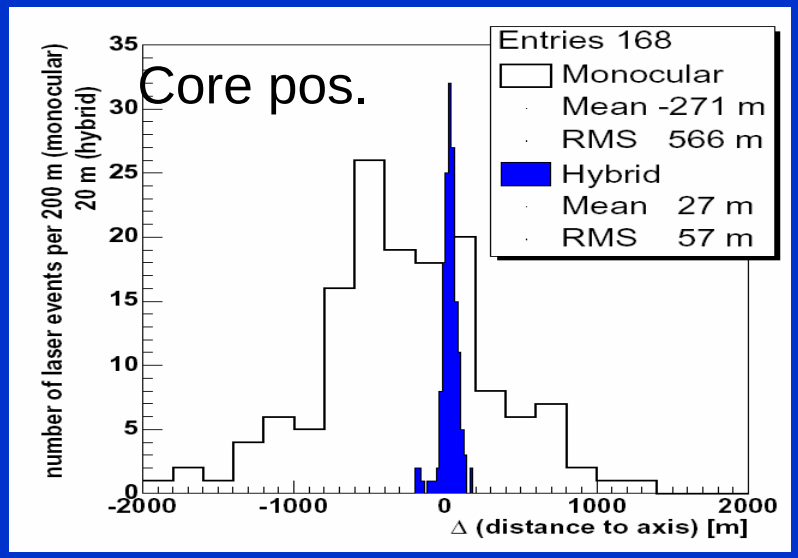
Coverage of Northern hemisphere is limited.

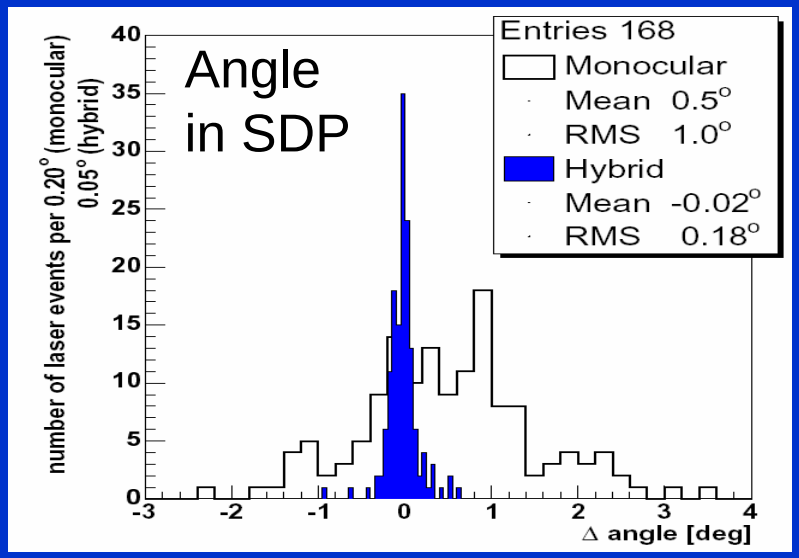
Hybrid Events

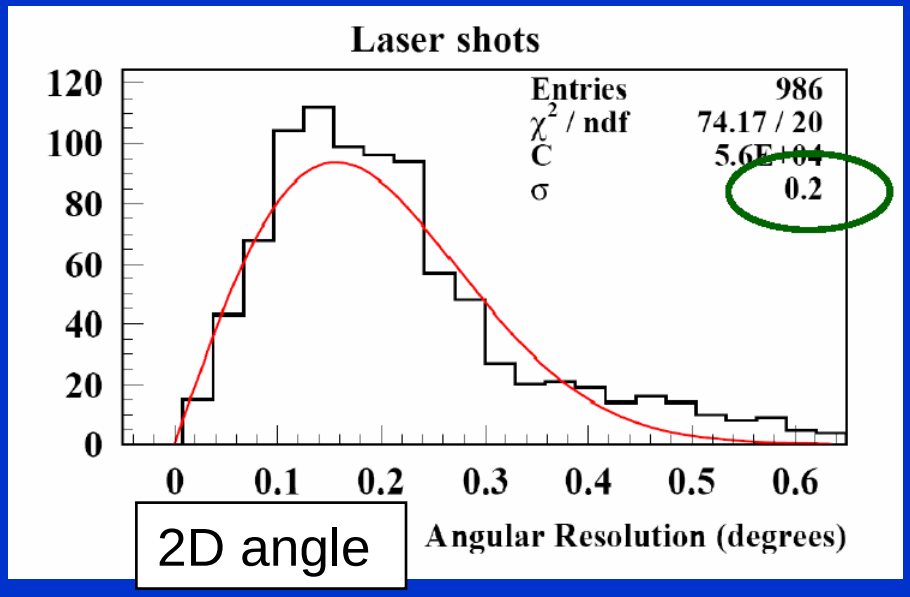


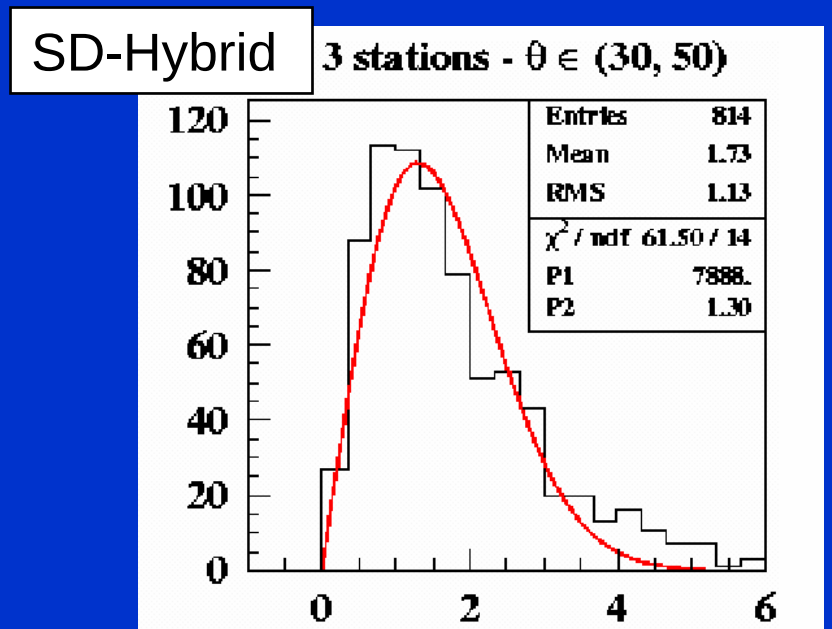
- Reconstructed
  - 1800/month
  - Total = 10,000
  - Mostly at low energies near eyes
  - ~2000 with energies above 1 EeV

Hybrid Core position and direction resolution is measured with CLF Laser shots









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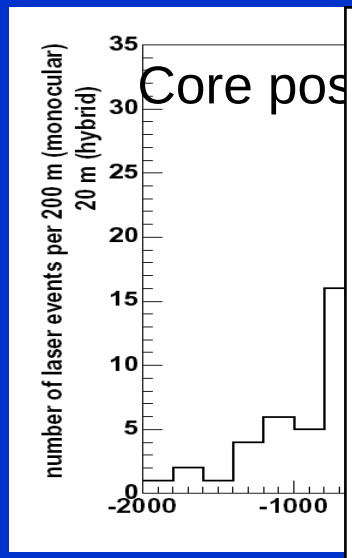
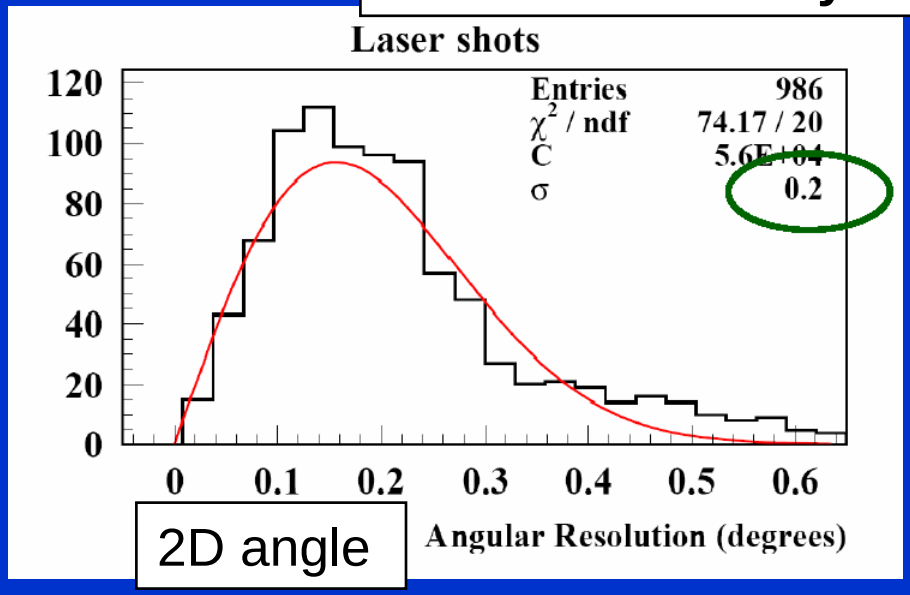
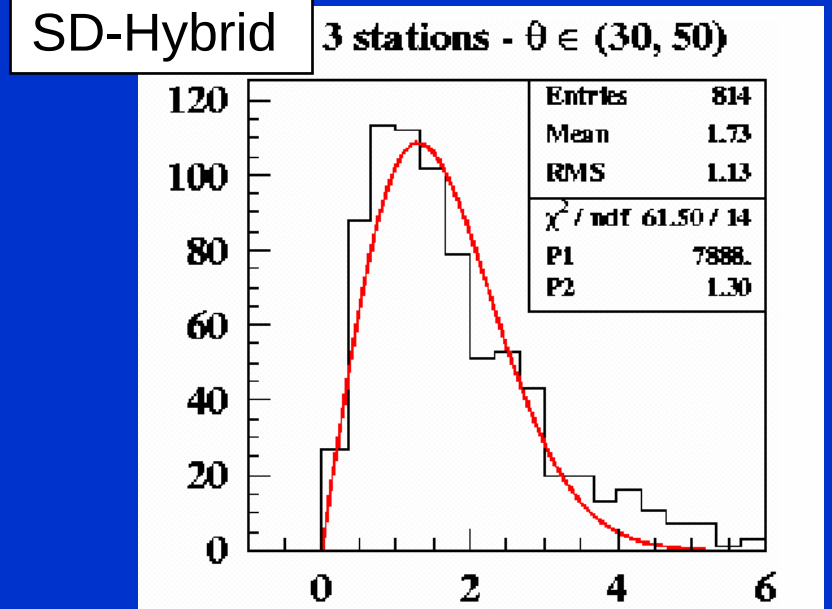
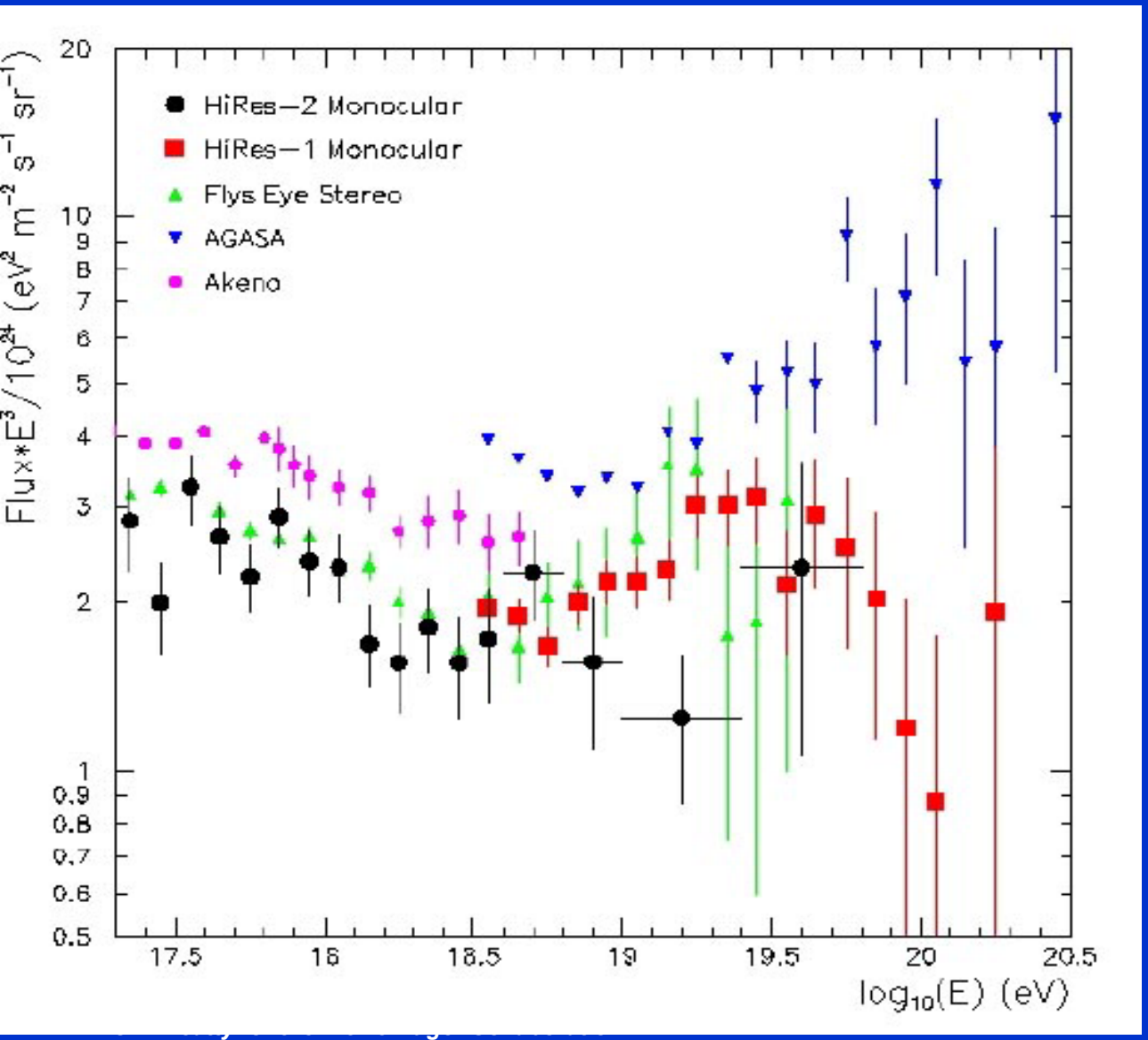


- **Angular resolution (68% CL):**
  - **Hybrid – *0.6 degrees***
  - **Surface array**
    - ***2.2º for 3 station events (E< 4 EeV, θ < 60º).***
    - ***1.7º for 4 station events (3<E<10 EeV)***
    - ***<1.4º for 5 or more station events (E>8 EeV)***
- **Core position**
  - **Hybrid – *60 meters***
  - **Surface array: < 200 meters**





The GZK Feature?



- **AGASA (SD) sees the apparent continuation of the spectrum**
- **HiRes (FD) a dropoff in the spectrum above 10^19.5eV.**

FD-alone Energy Measurement

- **Pro: The energy measurement is calorimetric.**
  - **Energy~ionization loss~tracklength~fluorescence emission**
- **Cons:**
  - **Low duty cycle**
  - **The aperture is not easily determined. For example, if the atmosphere is dirtier than expected:**
    - ***Energy is underestimated.***
    - ***Exposure (integrated trigger efficiency) is overestimated.***
    - ***With enough time and modest money spent on atmospheric monitoring, this problem can be mitigated.***

SD-alone Energy Measurement

- **Con: The energy measurement technique relies on MC simulations of the expected signal level**
  - **Assumed hadronic interaction model requires extrapolations of collider data to higher energies and rapidities. Uncertainties are difficult (impossible) to estimate.**

- **Pros:**
  - **high duty cycle**
  - **Exposure is easily estimated**
    - ***The array trigger efficiency is 100% for large showers!***
  - **self-calibration with atmospheric muons**

The Auger Model-Independent Approach

Use the strengths from each technique:
FD(Hybrid) energy, SD statistics, SD exposure.

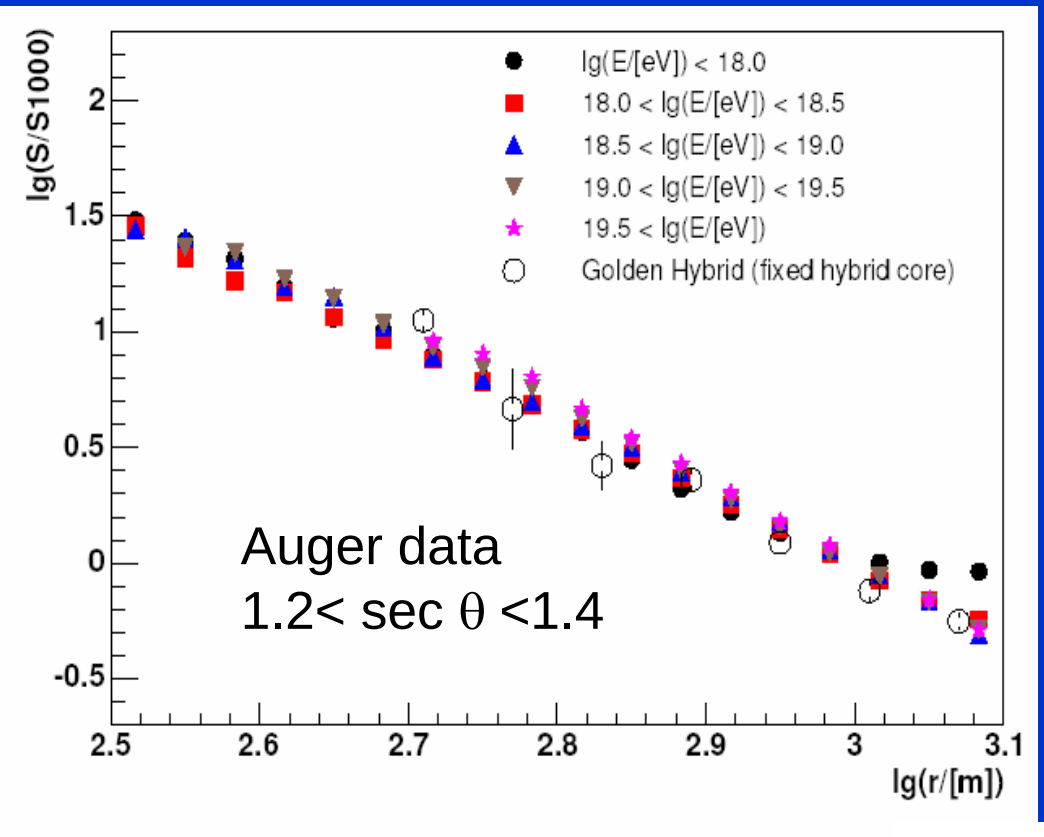
- **From SD data, reconstruct a stable ground parameter S(1000) (SD signal at 1000m) which is correlated with shower energy**

- **Empirically determine the S(1000)→Energy conversion**
  - **Measure the zenith angle dependence of the converter using SD data, and also using Hybrid data**
  - **Use Hybrid data to:**
    - ***Normalize the converter assuming the FD (hybrid) energy scale***
    - ***Determine the energy dependence of the converter***

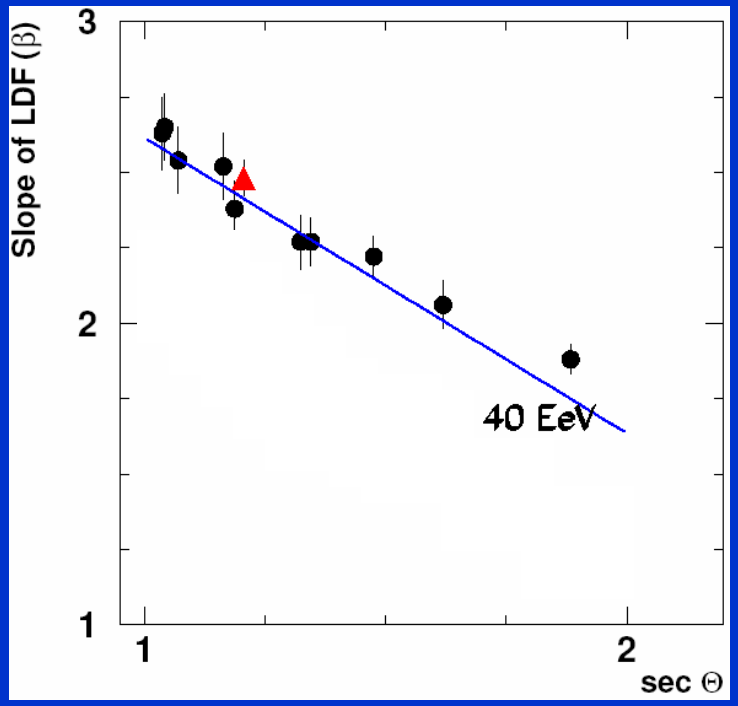
- **Divide the SD energy histogram by the SD exposure to obtain the measured spectrum.**

The SD fitting function is determined from the data

- **LDF: Distribution of signals versus the core distance r (transverse distance of detector to the shower axis)**



Use a "NKG-like" LDF ~ $r^{-\beta}$



Measured $\beta(E,\theta)$ directly from the data.

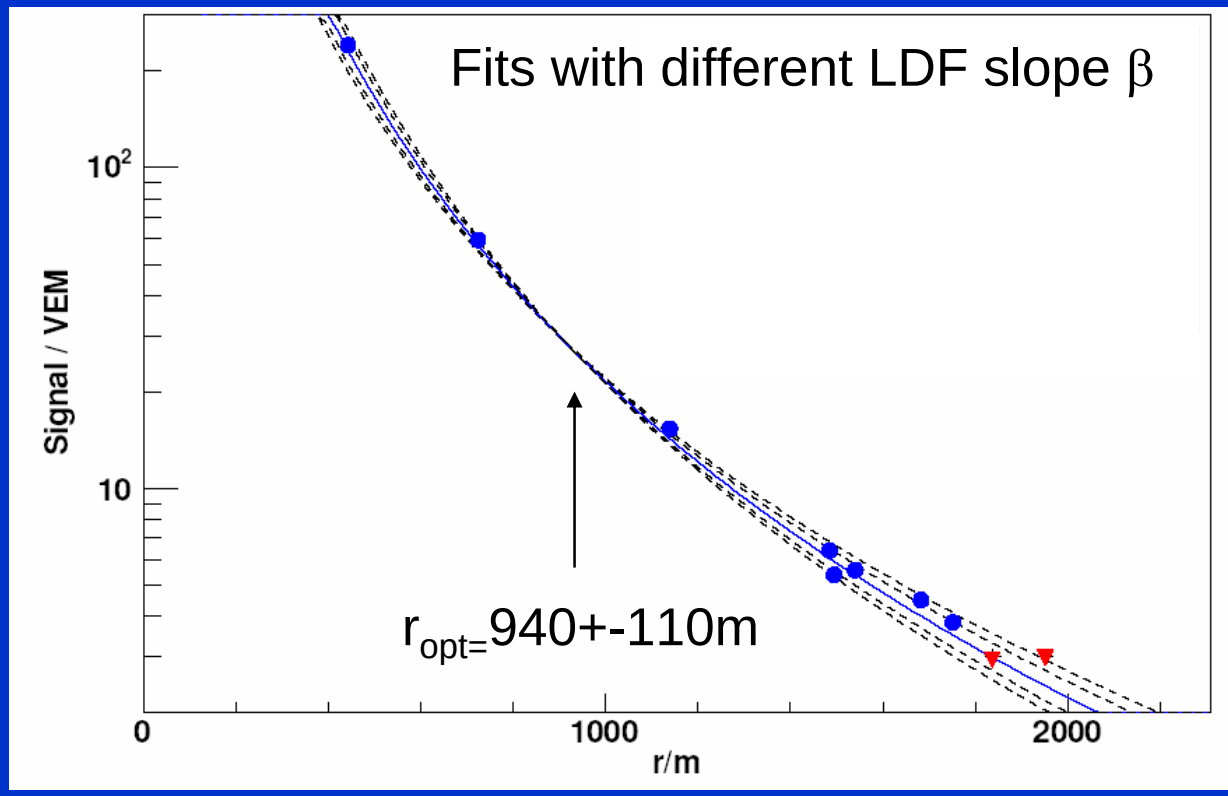
σ_β ~ 10% from previous exps.

The Ground Parameter S(1000)

- **To determine the shower energy, a single ground parameter S(r) is traditionally chosen to minimize the effects of reconstruction errors, and shower-to-shower fluctuations**

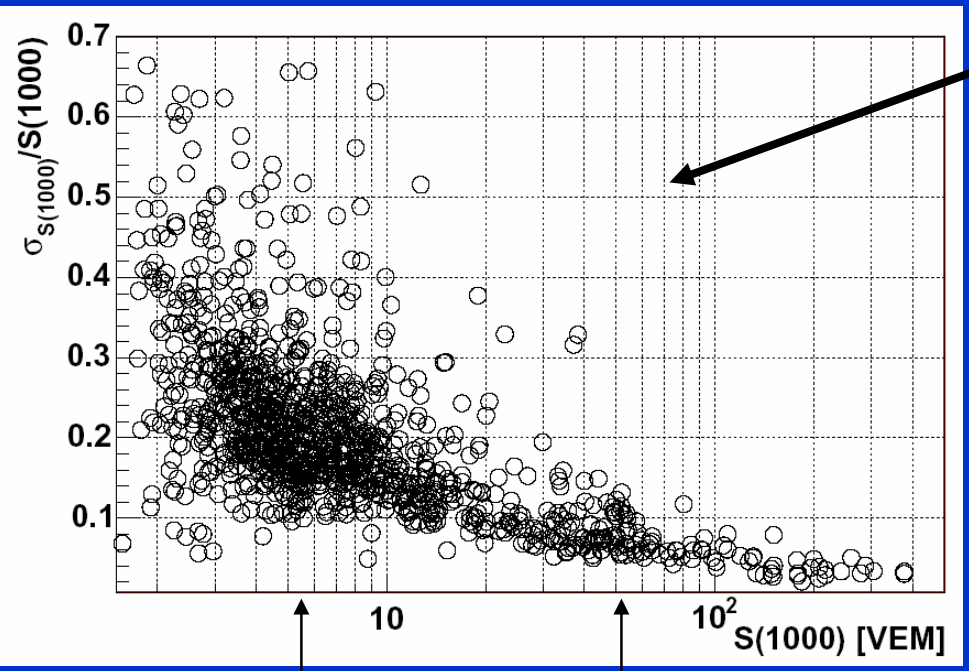
S(r) is determined from interpolating the data using a LDF with fixed β.

However, for most events, precise knowledge of the LDF shape is not important because there exists an optimal core distance $\mathbf{R_{opt}}$ at which the different fitted LDFs cross-over.



$S(r_{opt})$ is a stable ground parameter.

A fit to a NKG-like LDF function is used to extract simultaneously S(1000) and the core position

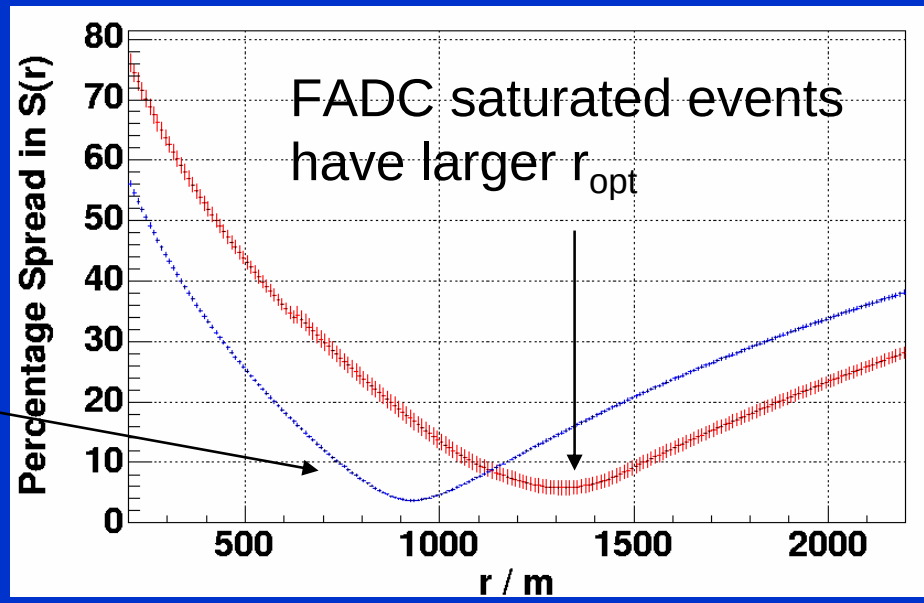


Statistical reconstruction error on S(1000).

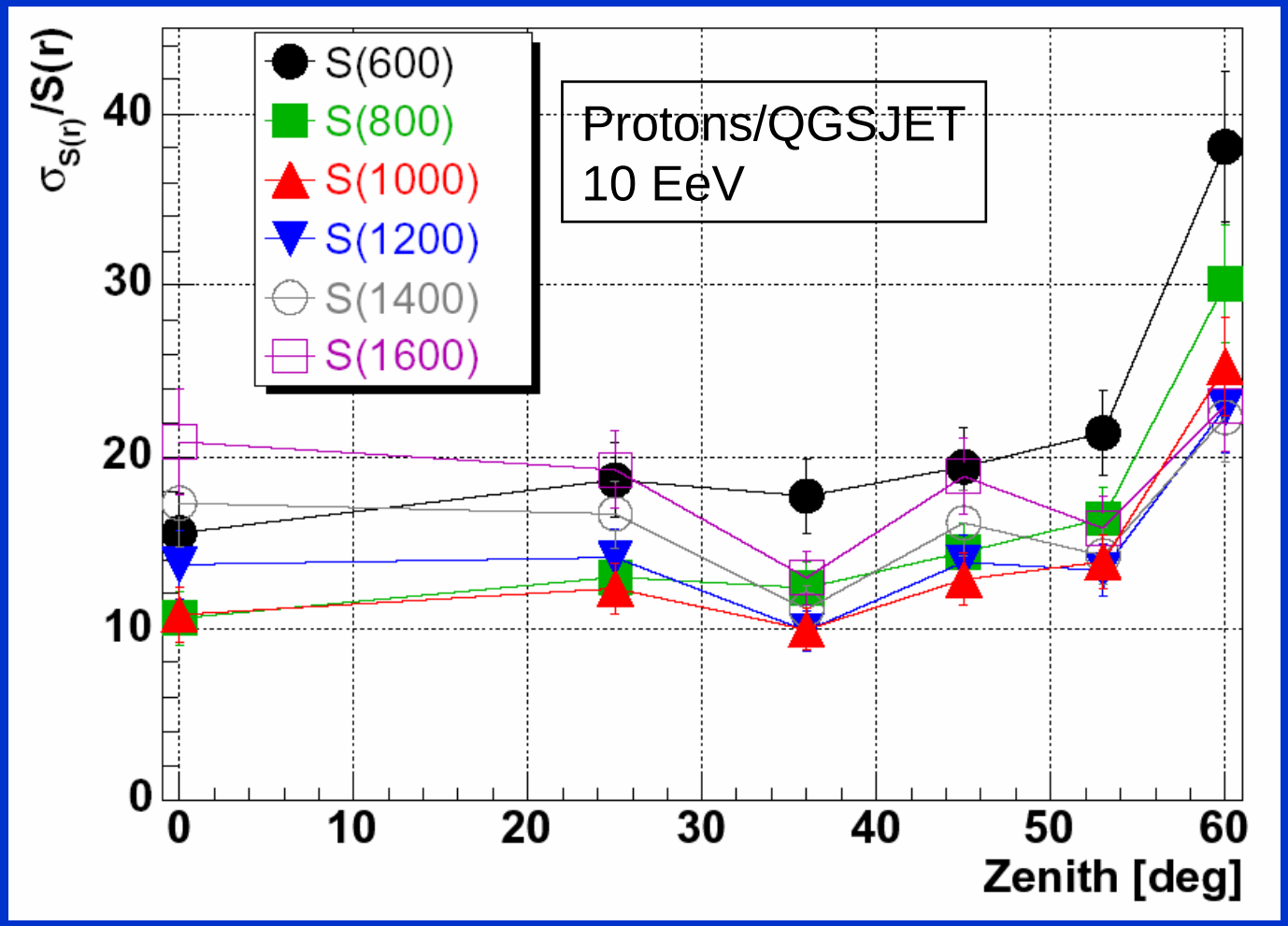
~1 EeV

~10 EeV

Systematic error from LDF shape <4%, estimated by varying LDF slope by +-10%.

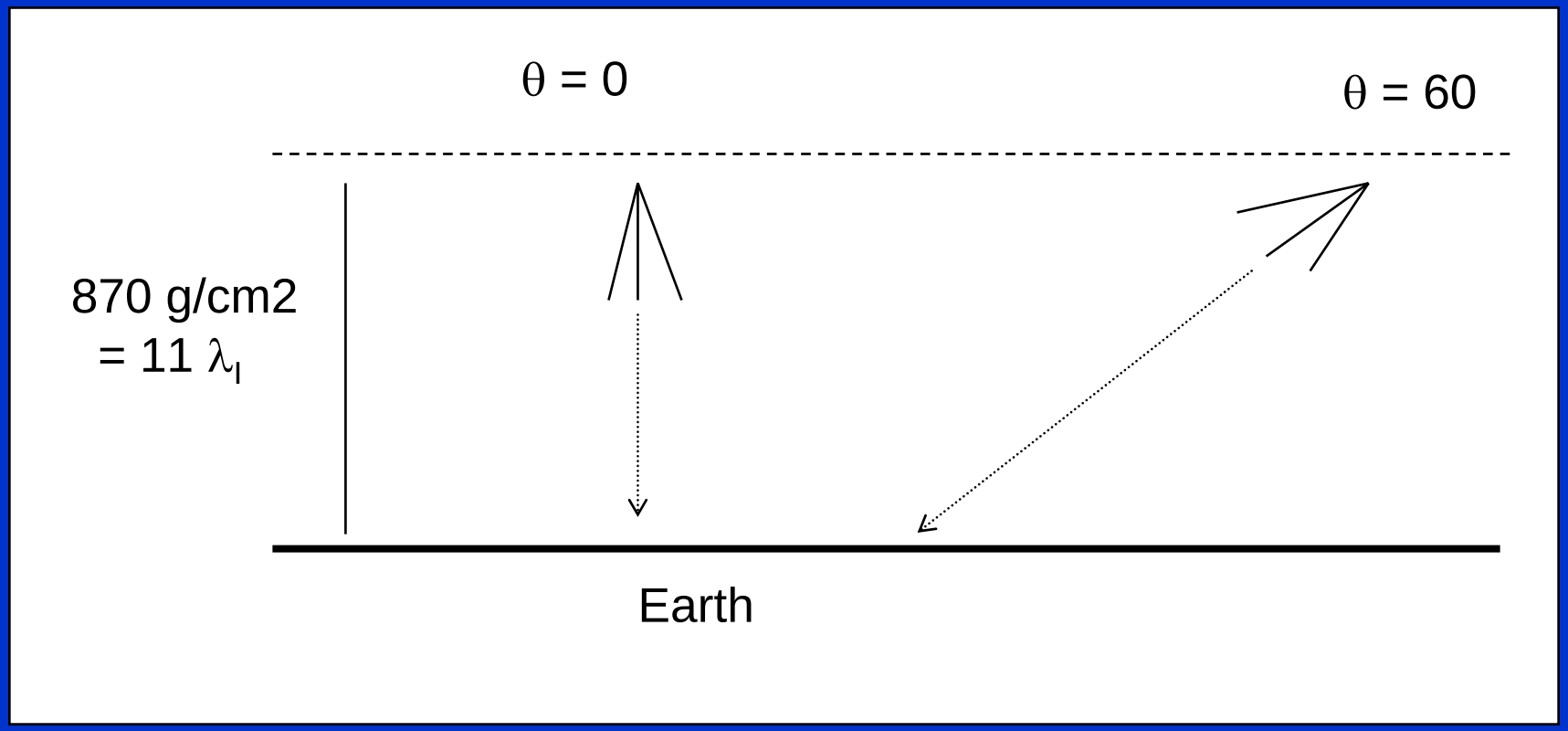


The total statistical fluctuations of S(1000) including shower-to-shower can be estimated with simulations



- **S(1000) is optimal for a 1.5km spacing array.**

Showers coming from different zenith angles give very different signals due to flux attenuation in the atmosphere

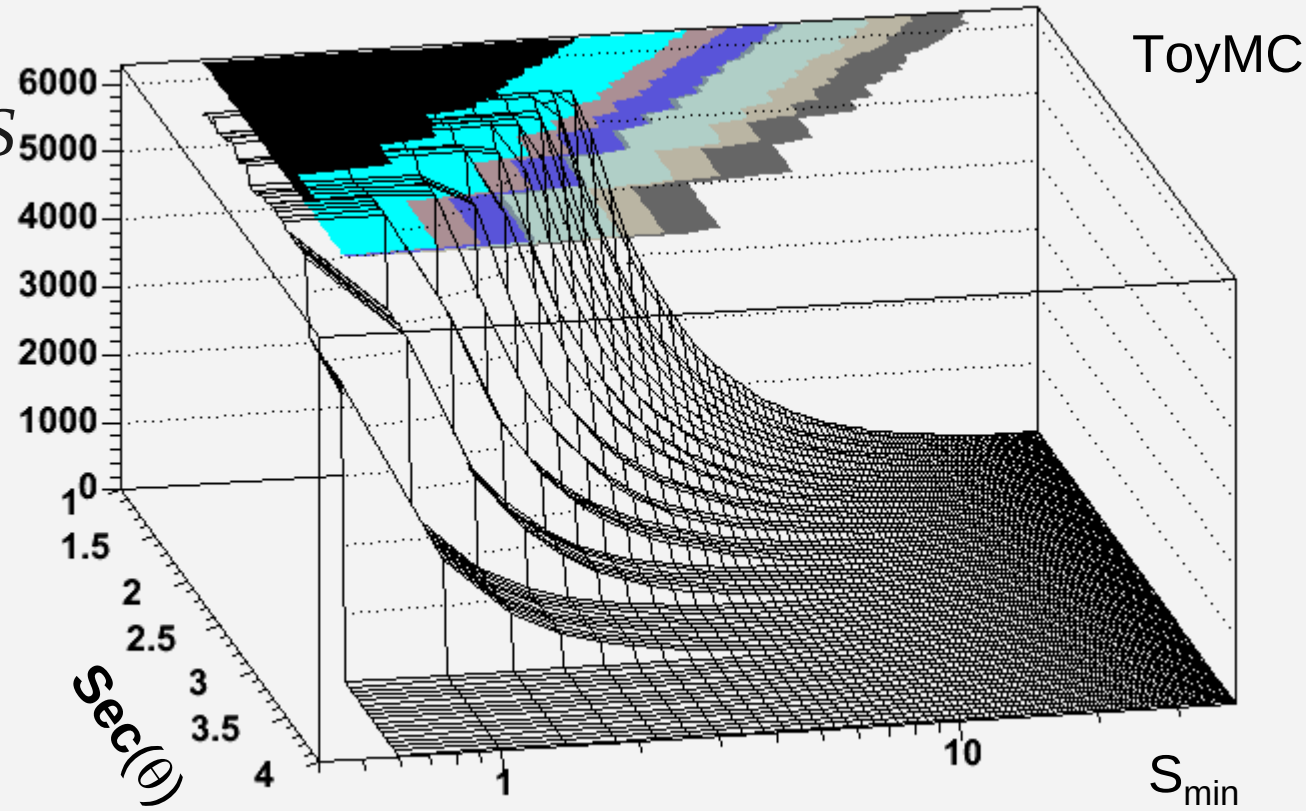


The "slant depth" is 870g/cm^2 * sec(θ)

Measure the θ Dependence directly from the data

$$\int_{S_{\min}}^{\infty} \frac{dN}{dS \cdot d\sin^2\theta} dS$$

$\propto \cos\theta \cdot d\Omega$
(acceptance correction)



- The flux dN/dS can in principle be measured independently in each zenith angle bin.
- Because dN/dS falls monotonically with increasing S, and because the CR flux is isotropic to a good approximation, the contours of constant integrated flux intensity give the θ dependence of the S(1000)→Energy relationship.

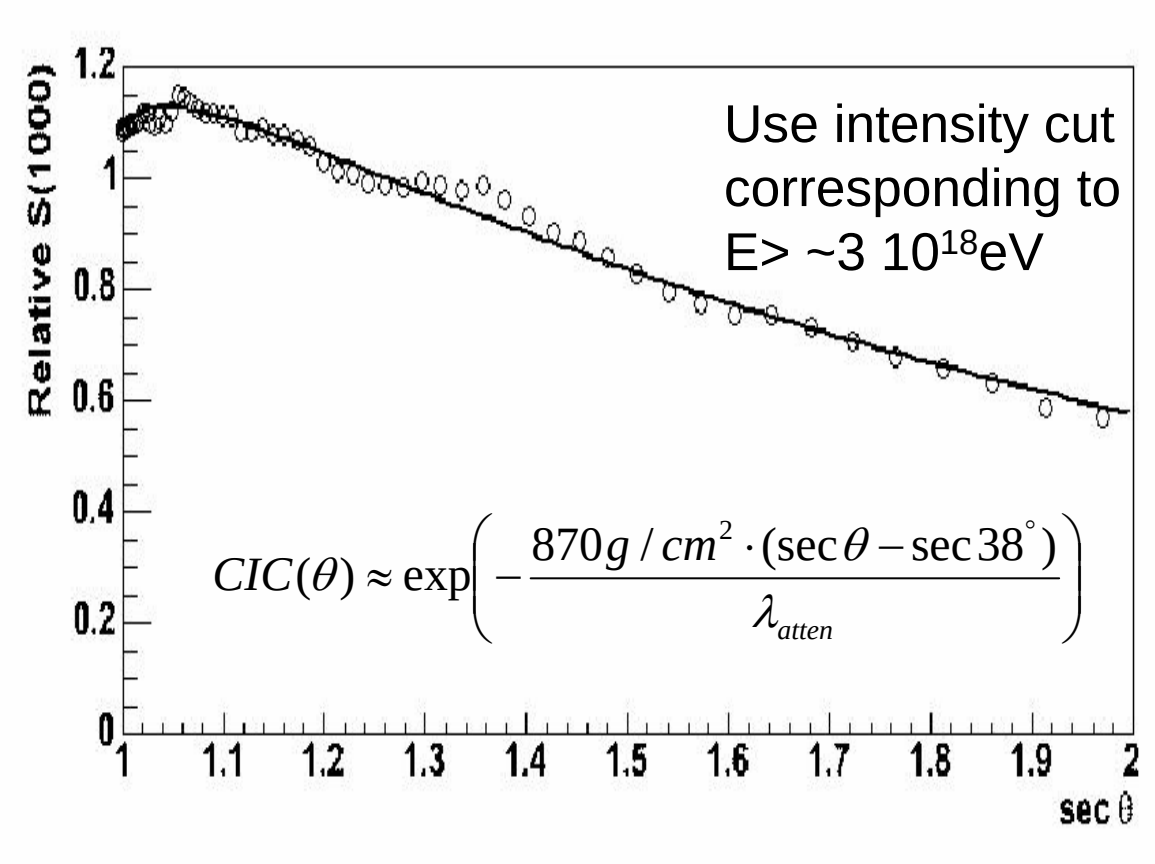
The SD-measured θ dependence (Constant Intensity Cut method)

- Shape is scanned in θ using bins of $\Delta\sin^2(\theta)=0.1$
- Normalize at the median zenith angle of 38 degrees.

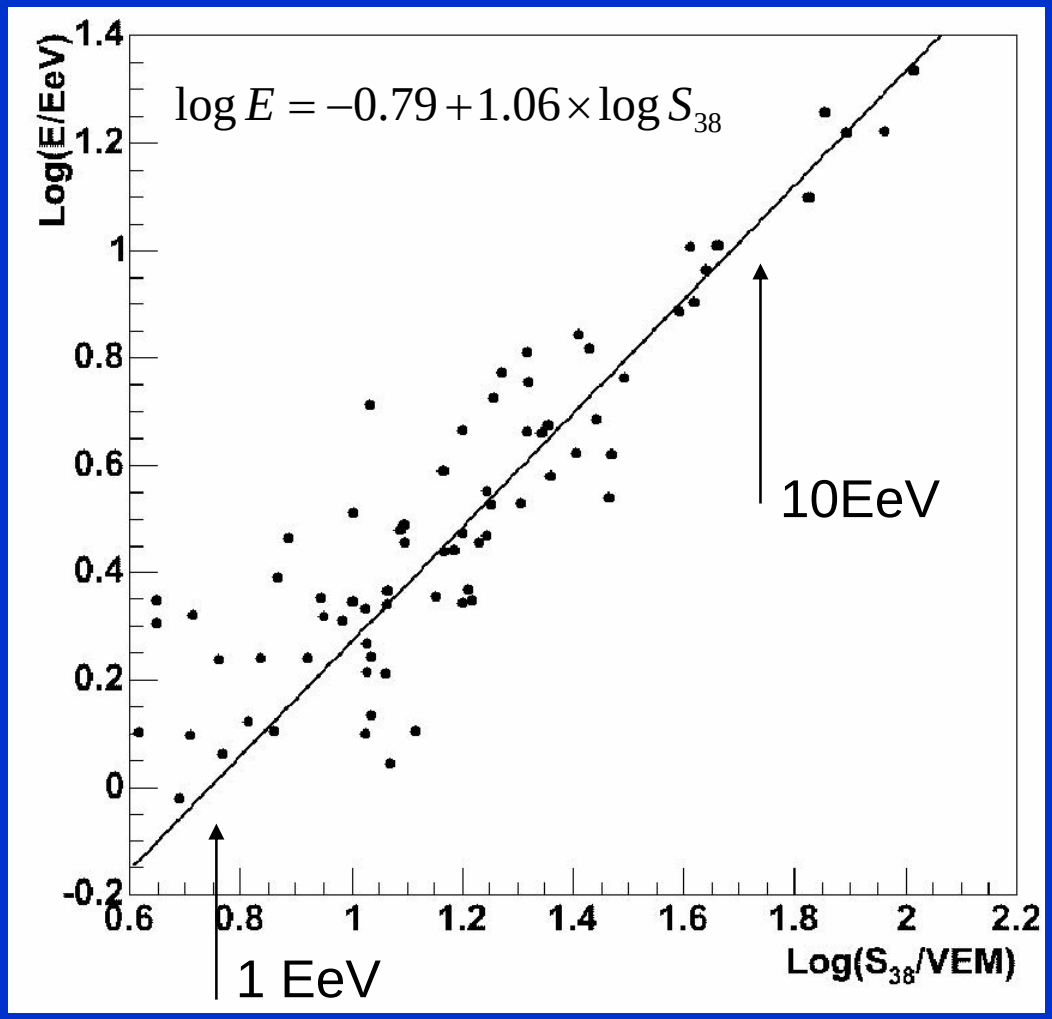
$$S(1000)_\theta = S_{38}(E) \times CIC(\theta)$$

- **Assume for now that CIC(θ) is independent of energy.**

Note: bins are correlated!



Obtain the S38→Energy Correlation with Fluorescence energies from hybrid events

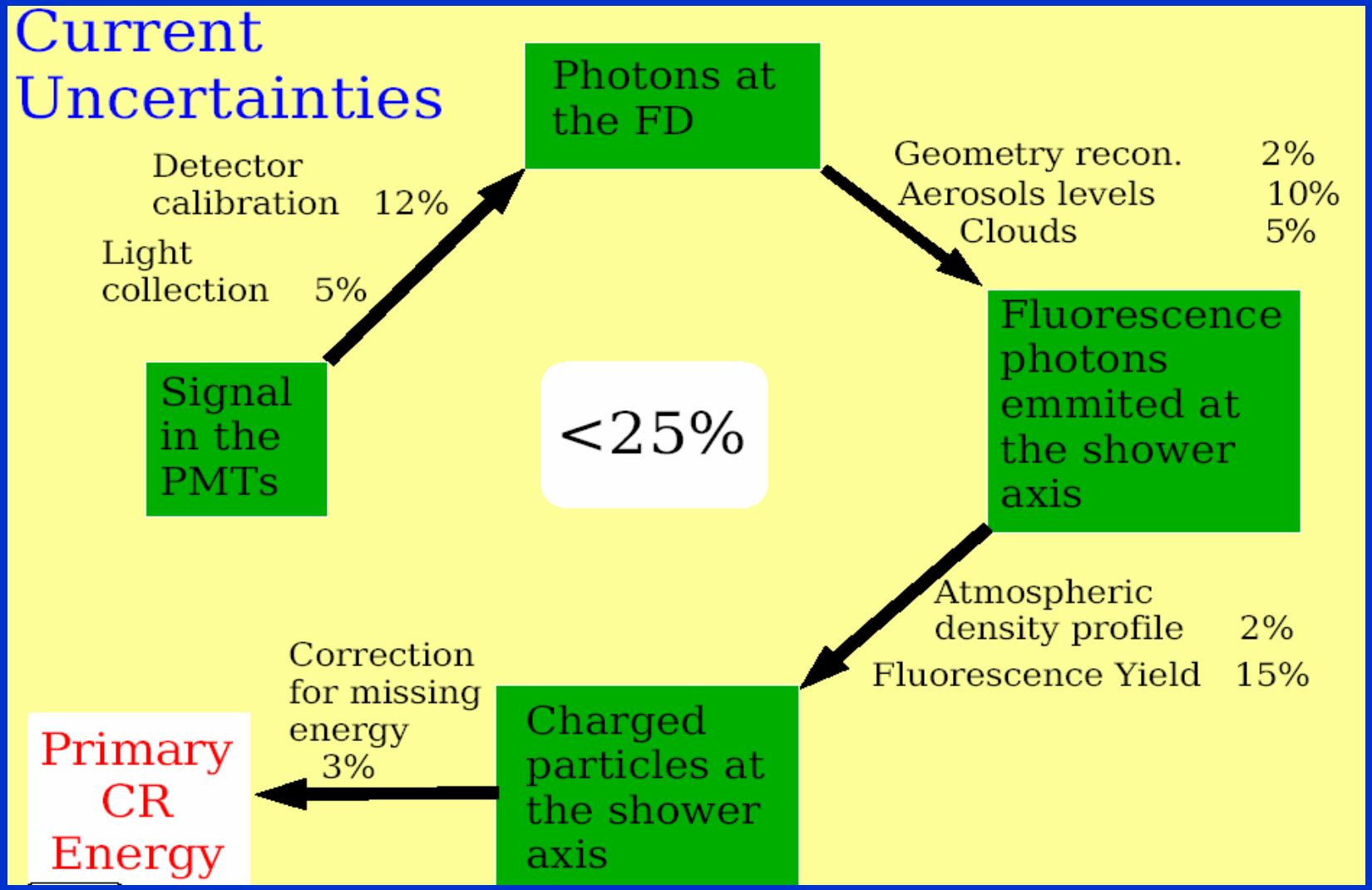


- Strict event selection:
  - tracklength >350g/cm^2
  - Cherenkov contamination<10%
- Obtain converter:

$$E/EeV = 0.16 \times \left(\frac{S(1000)/VEM}{CIC(\theta)} \right)^{1.06}$$

- **Note: systematic error grows when extrapolating this rule to 100 EeV!**

Systematic Errors in the FD(Hybrid) Energy Normalization



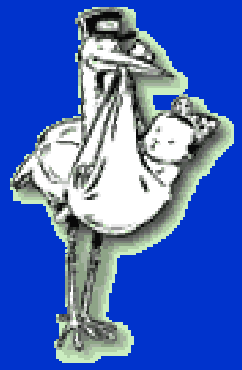
Summary of procedure

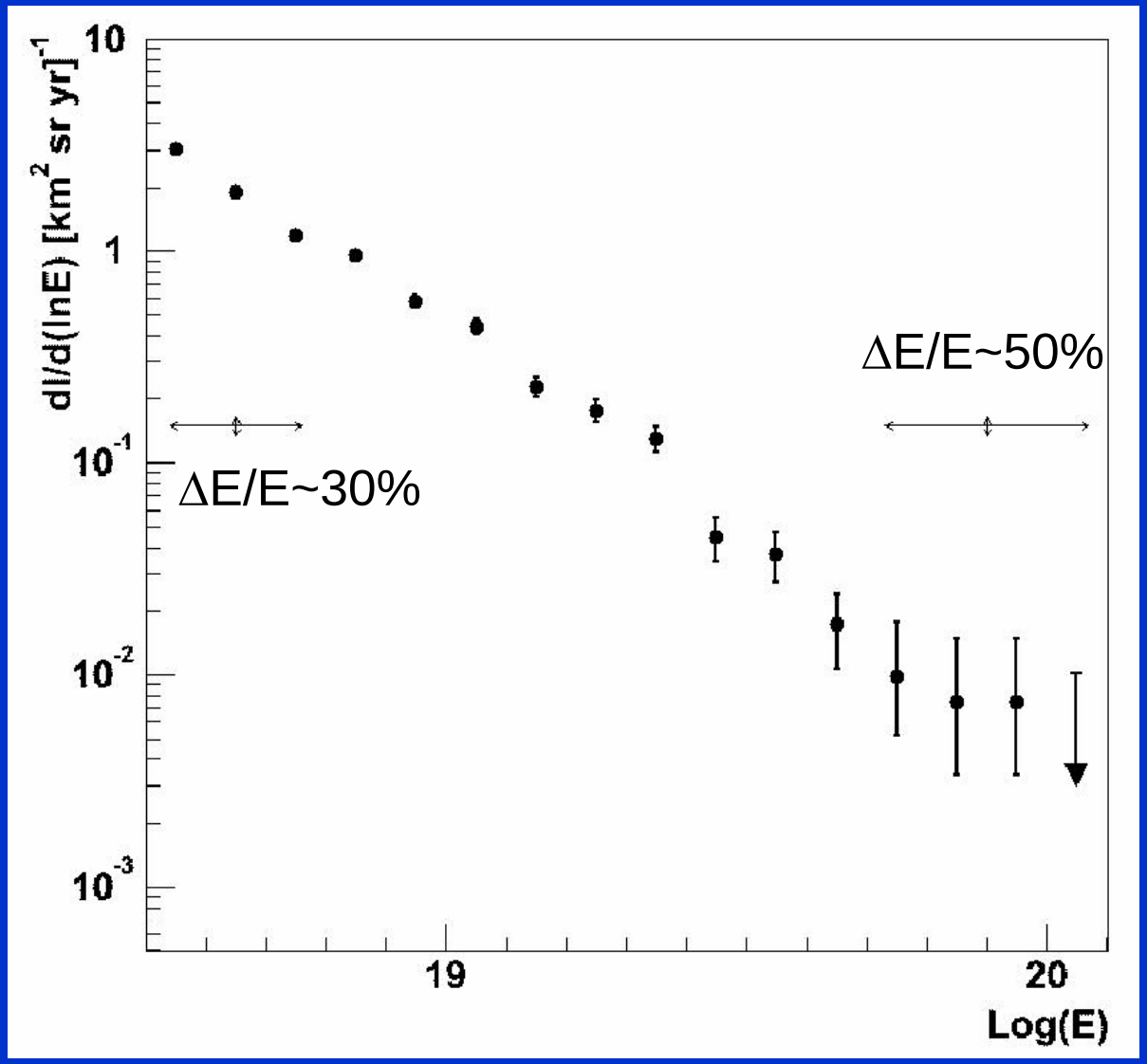
- **Reconstruct the ground parameter S(1000)**
- **Correct for the zenith angle dependence by converting S(1000) to S38 using the measured CIC curve.**
- **Convert S38 to Energy using the correlation determined with hybrid data**

Tank signals → S(1000) → S38 → Energy

Each step is empirically determined!

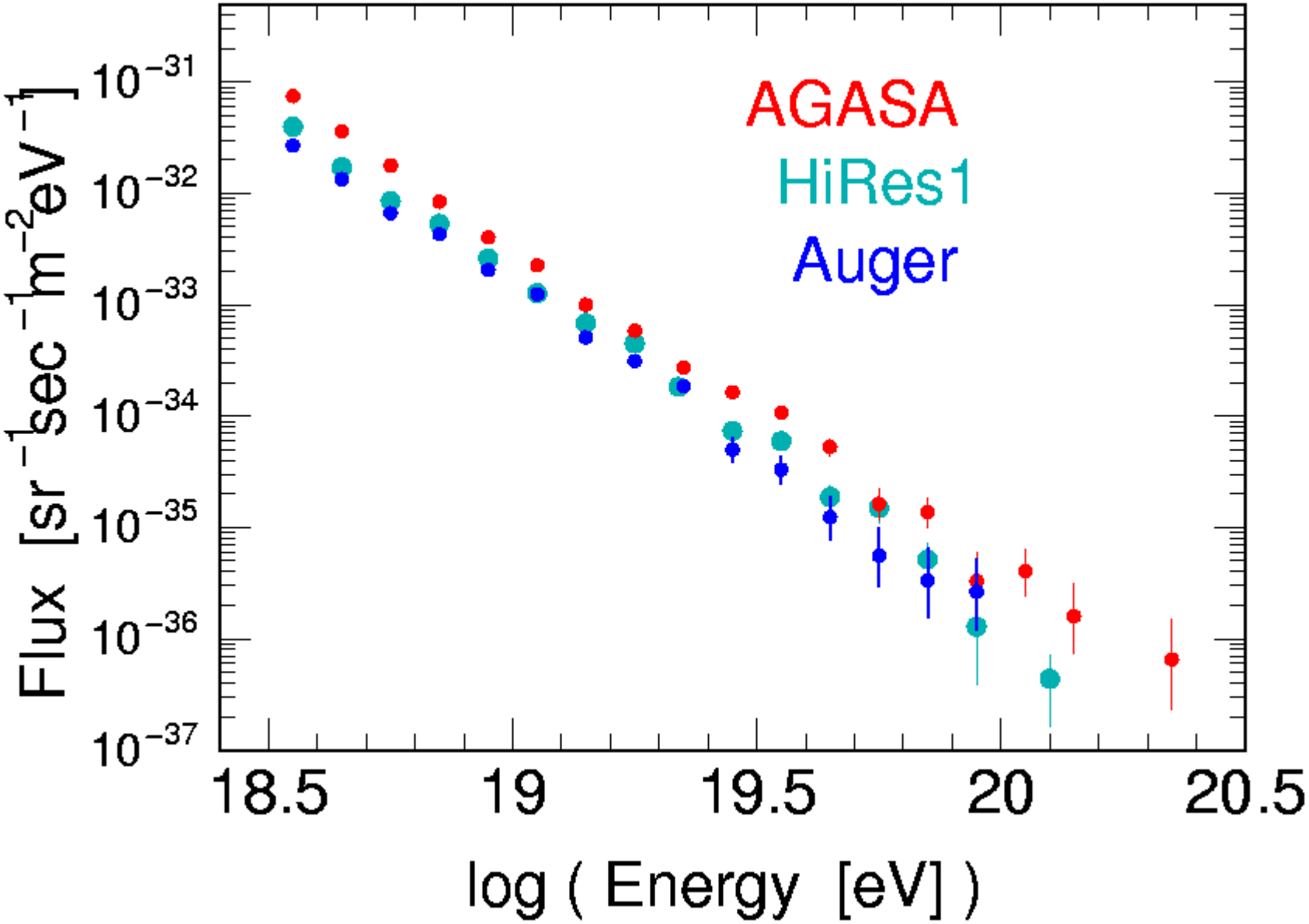
The Auger Southern Sky Energy Spectrum



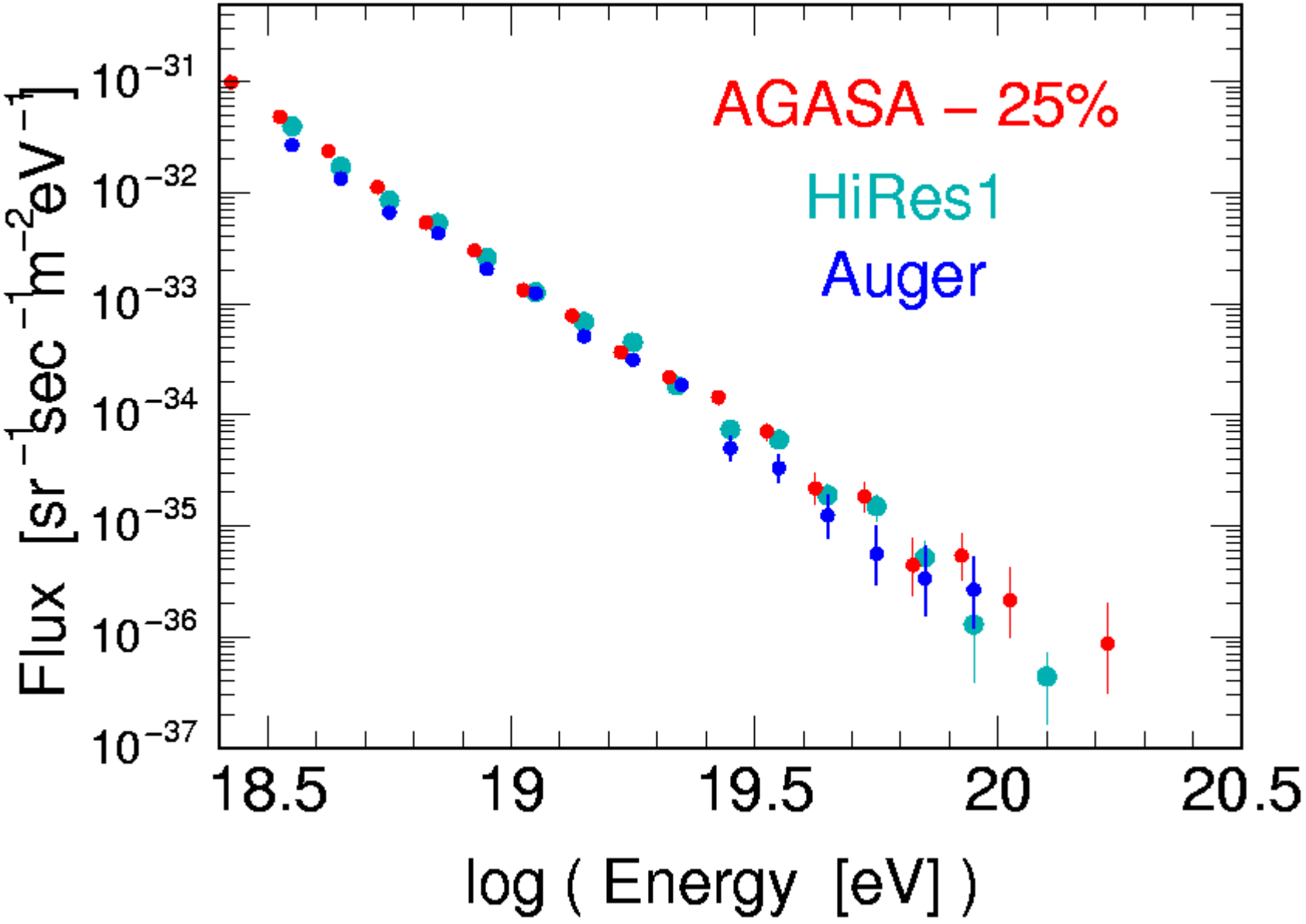


- dN/d(lnE) = E*dN/dE
- Errors on points are Statistical only
- Systematic errors are estimated at two energy regions
  - Energy measurement (horizontal)
  - Exposure determination (vertical)

Comparison with HiRes1, AGASA

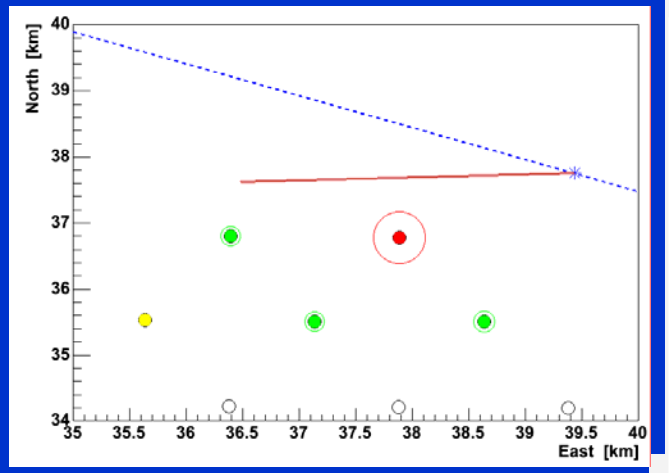


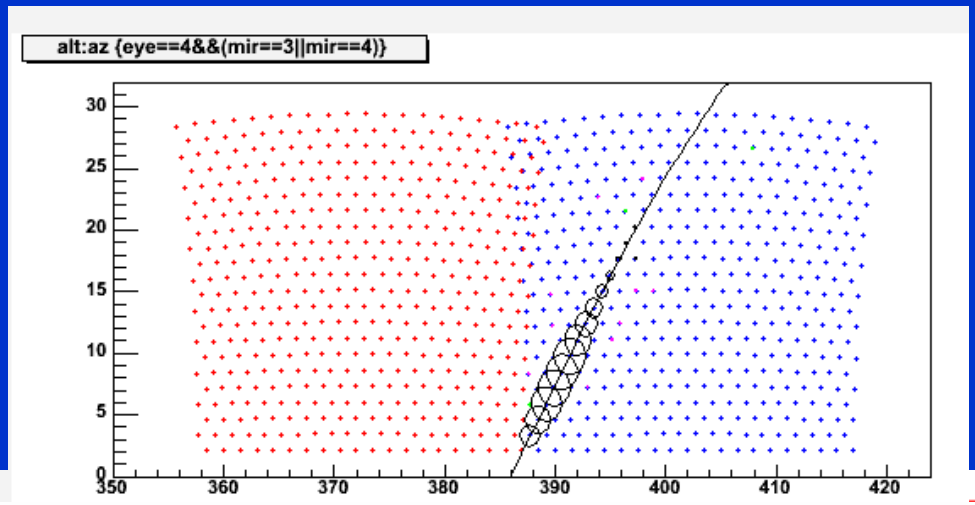
Comparison with HiRes1, AGASA-25%

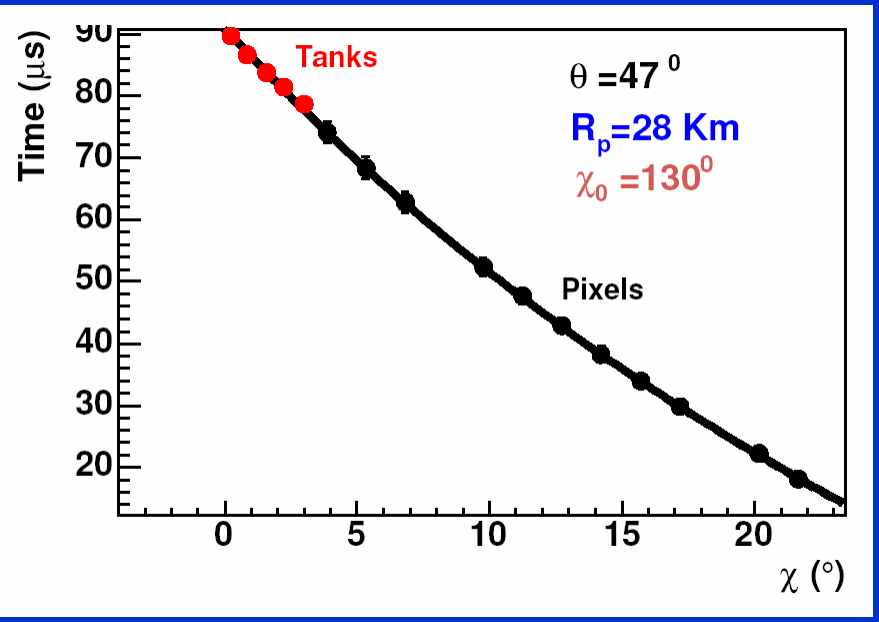


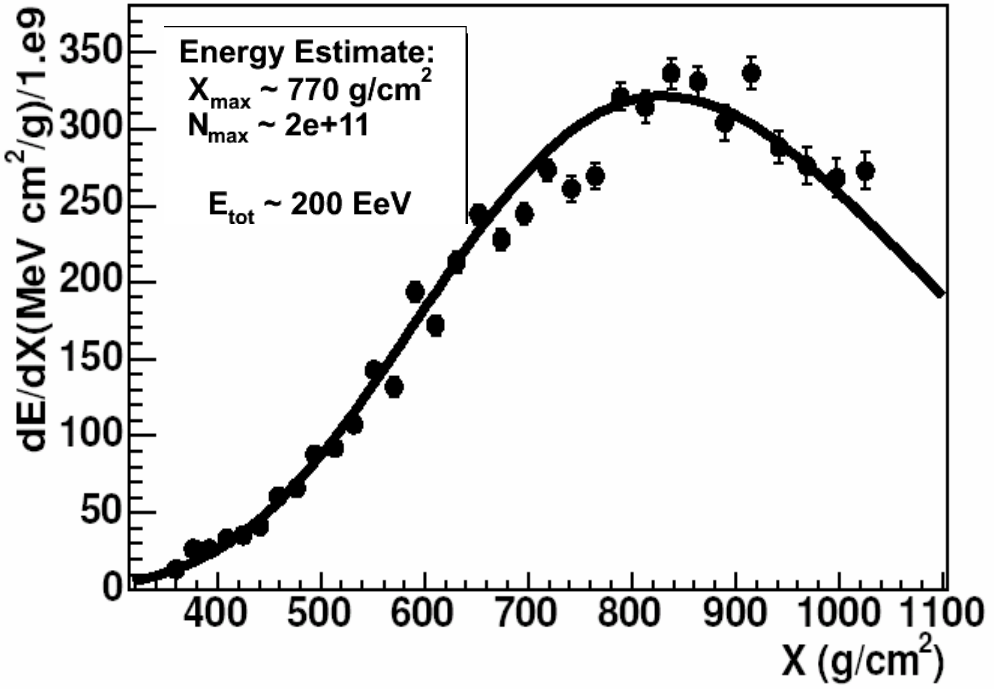
Our Highest Energy Event E_{FD}~2×10^{20}eV

Landed just outside the array, so not used in spectrum!









The Top 10 SD events

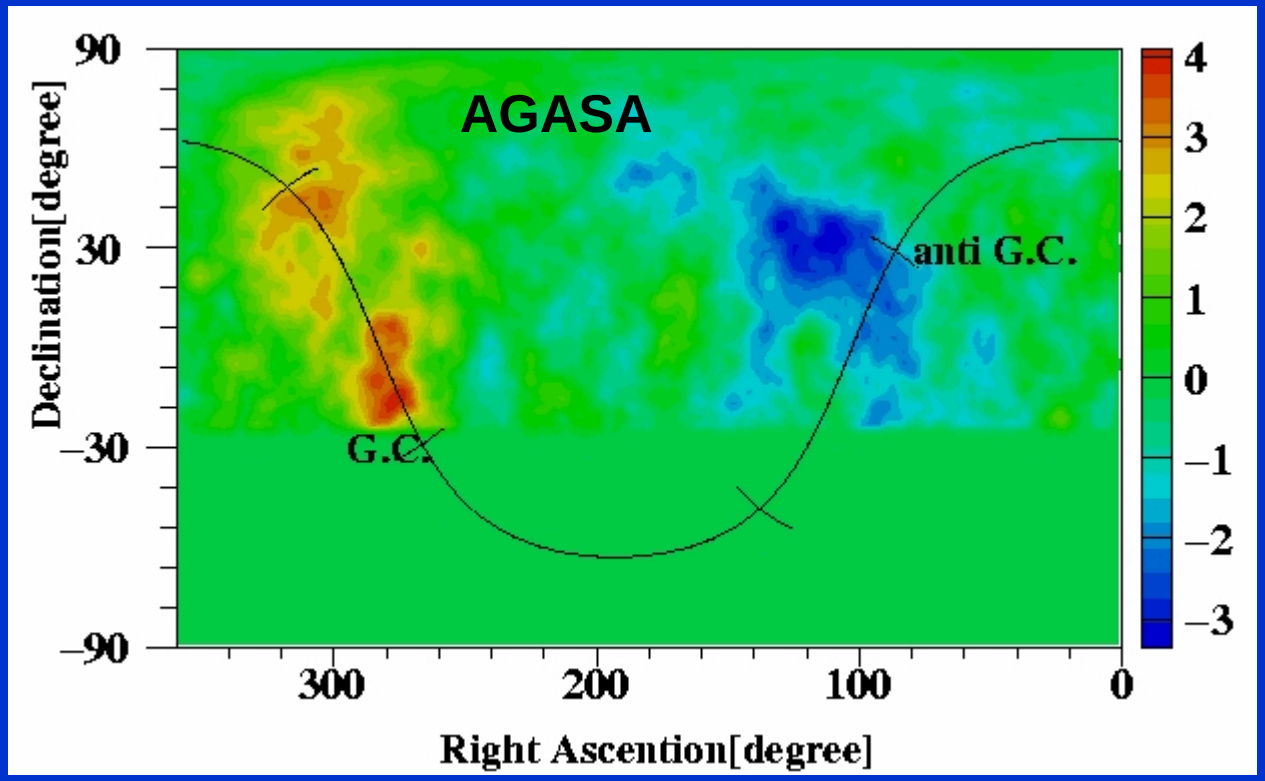
Event Id	θ	S(1000)	Multiplicity	r_{opt}	β	E(EeV)
1096757	45.1 ± 0.2	$344 \pm 15 \pm 33$	21	1322	—	86 ± 9
1225537	34.4 ± 0.2	$364 \pm 10 \pm 13$	14	909	2.48 ± 0.06	79 ± 4
787469	59.7 ± 0.2	$204 \pm 8 \pm 11$	31	1173	2.03 ± 0.06	76 ± 5
762238	47.3 ± 0.2	$248 \pm 11 \pm 12$	18	1135	2.22 ± 0.07	64 ± 4
1102721	23.8 ± 0.2	$318 \pm 22 \pm 52$	12	1467	—	63 ± 11
1233429	54.3 ± 0.2	$201 \pm 9 \pm 16$	21	1261	—	63 ± 6
1018639	26.9 ± 0.2	$294 \pm 19 \pm 26$	10	1196	2.93 ± 0.13	59 ± 6
1264145	16.3 ± 0.2	$289 \pm 12 \pm 11$	11	910	2.65 ± 0.11	56 ± 3
1263529	20.7 ± 0.2	$264 \pm 20 \pm 34$	7	1470	—	51 ± 8
634746	51.6 ± 0.2	$174 \pm 9 \pm 12$	14	1203	—	48 ± 4

Reconstruction errors only

Anisotropies

- **It is extremely difficult to measure anisotropies in the sky which populate a narrow energy band in a rapidly falling energy spectrum.**
  - The energy search window must be carefully tuned to coincide with the true energy band of any excess. Otherwise the isotropic lower energy background swamps the signal.
  - Systematic errors in the energy measurement can easily contaminate the population of the energy window.
  - Precise angular resolution is needed to detect sources with small intrinsic angular scales. Otherwise the off-source background flux dominates.
- **Furthermore, low statistics require that the energy and angular windows be pre-defined so that the statistical significance of excesses can be evaluated**

Previous Observations of the Galactic Center



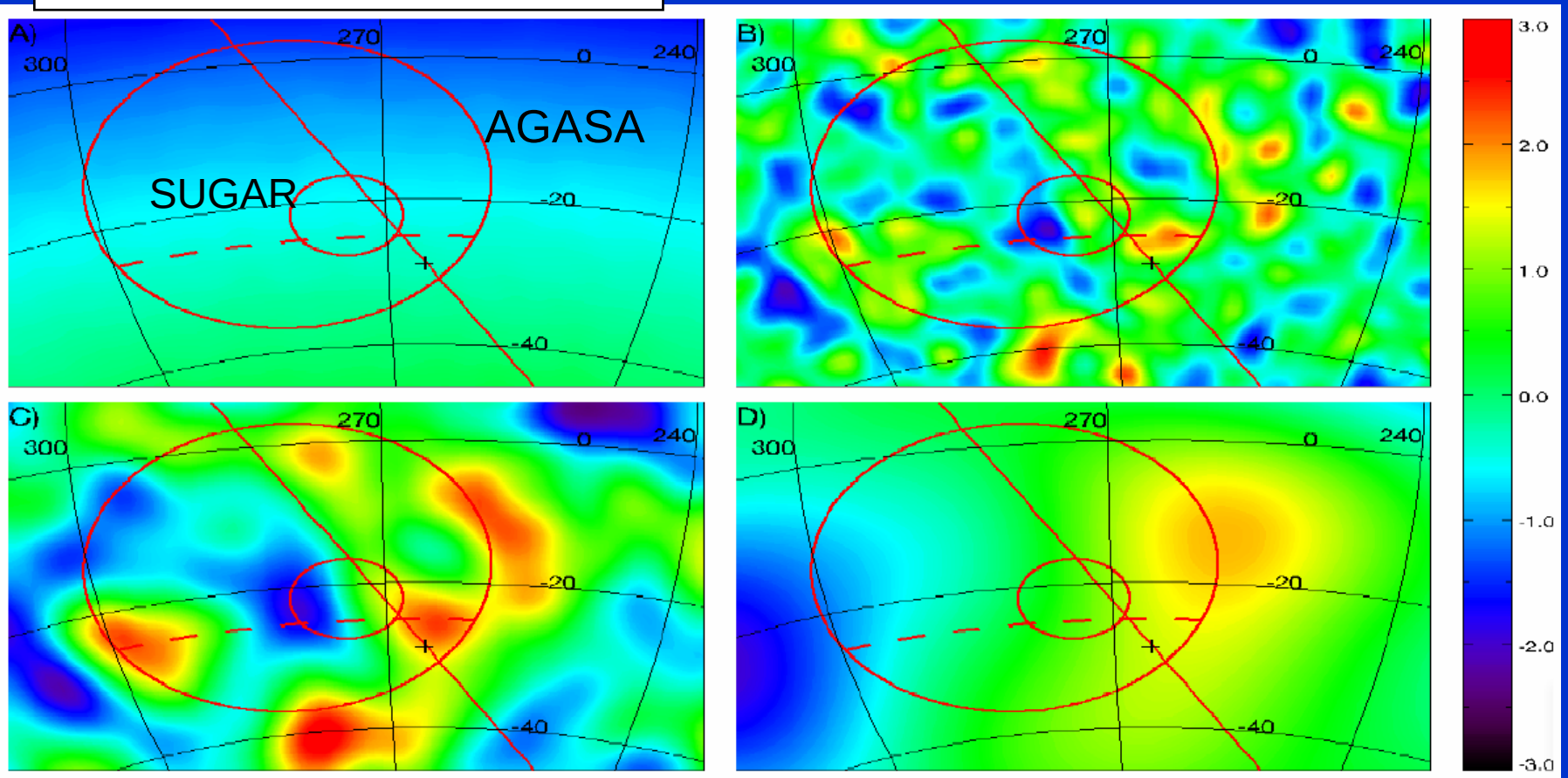
- 22% excess seen at 4.5σ by AGASA with a partial 20 degree tophat window (centered near the GC) with E=1-2.5EeV.
- SUGAR sees a 2.9σ excess with a 5.5 degree window at a slightly different location near the GC with E=0.8-3.2EeV.

•To propagate through the Galactic magnetic fields, the particles are postulated to be neutral, and perhaps to be neutrons from p-p scattering.

Auger: No excess seen in either region

Coverage map by shuffling event zenith, day, hour

Events smoothed with true resolution, Energy = 0.8-3.2 EeV



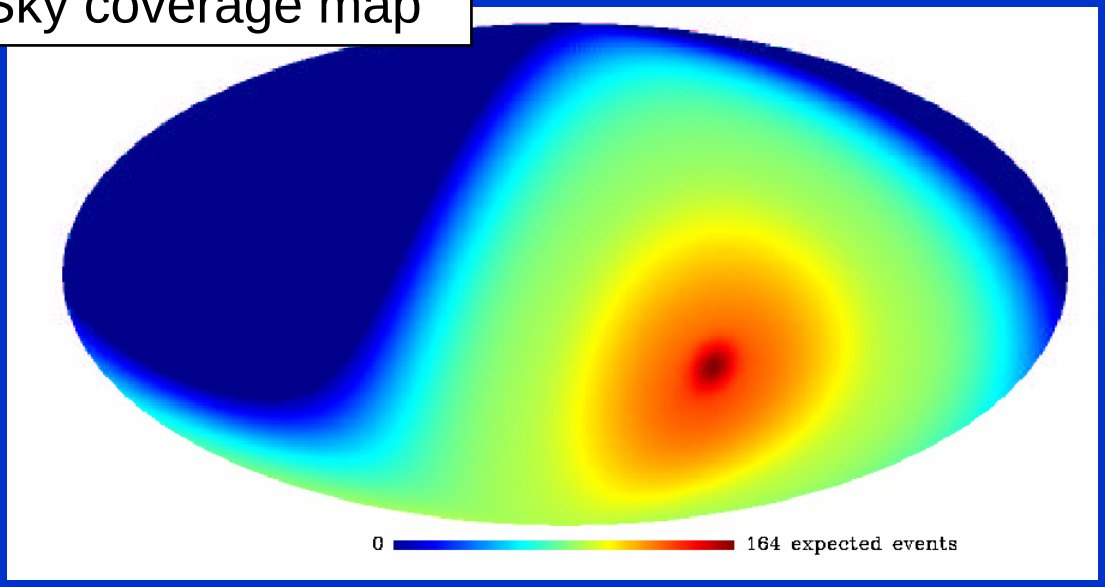
Smoothed at SUGAR scale, SUGAR energy window

Smoothed at AGASA scale, AGASA energy window

Search for localized excesses

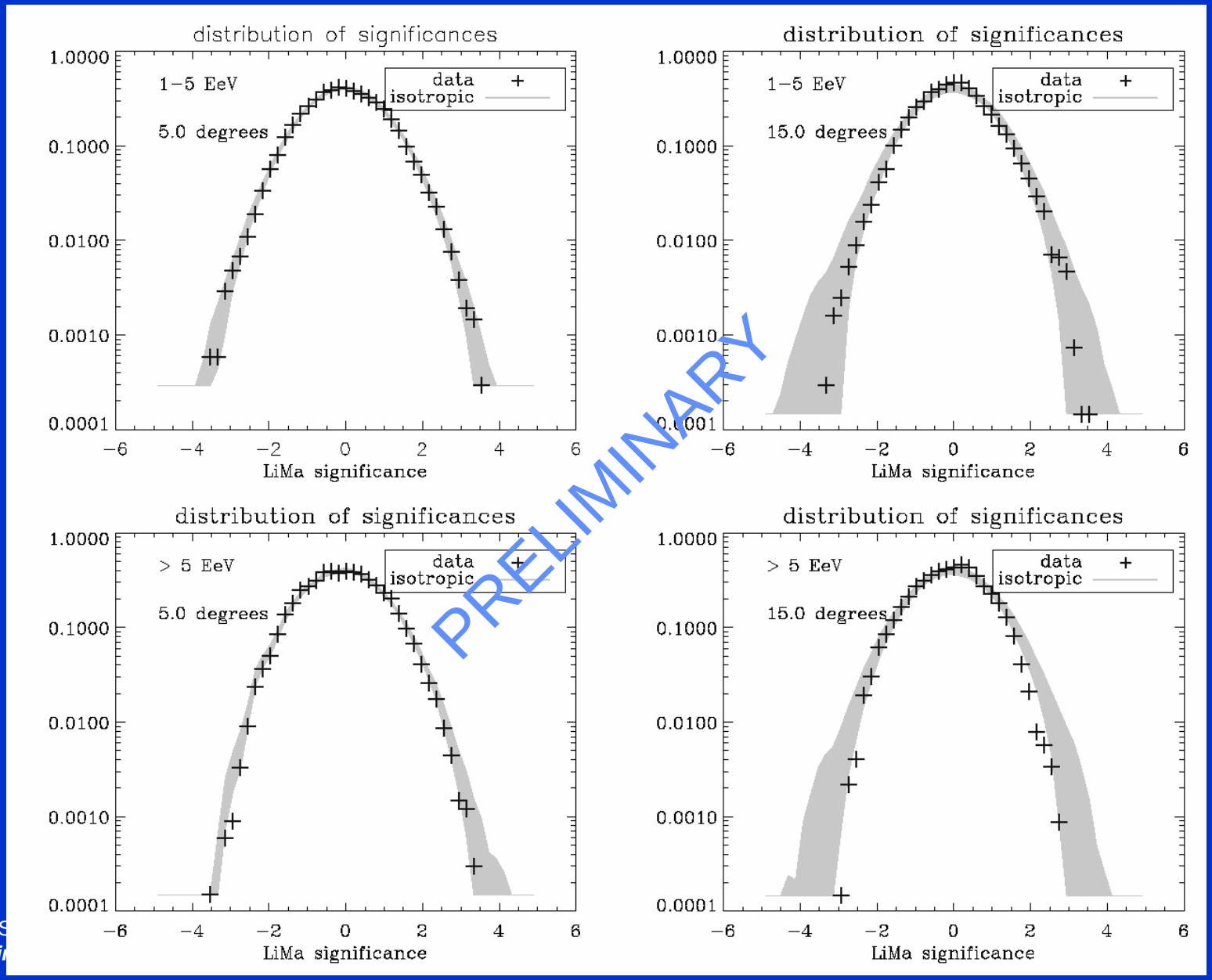
- **Predefined search parameters:**
  - **E=1-5 EeV, or E>5 EeV**
  - **Angular scale=5 degrees, or 15 degrees (tophat)**
  - **Uses Monte Carlo energy converter instead of CIC (for now)**

Sky coverage map



Look for excesses with tophats centered on each of 50K HEALPIX pixels (1 square degree)

So far, the data is consistent with isotropy



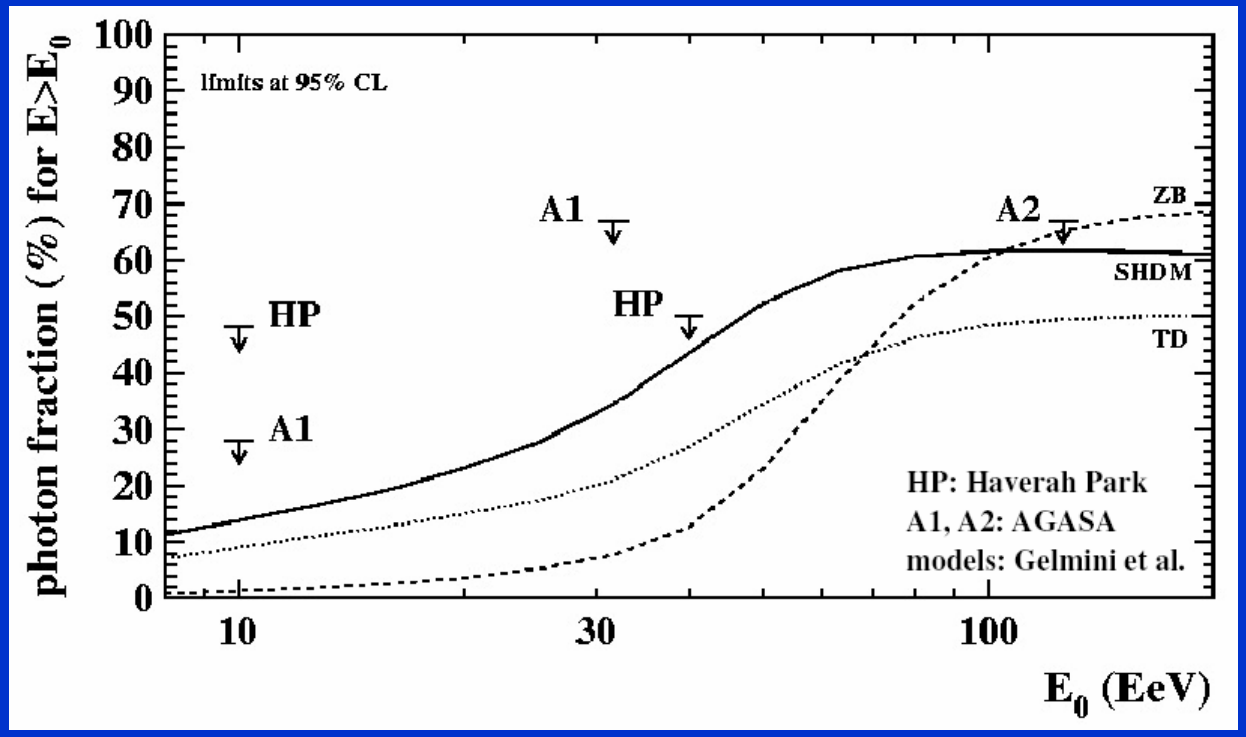
Other pre-defined targets not seen either with any large significance.

Target	$\ell(°)$	$b(°)$	Radius	$\log(E/\mathrm{EeV})$	Found	Exp.	Prob	Req. Prob
GC 1	0.00	0.00	15°	$\geqslant 18$	155	167.3	-	0.0035
GC 2	0.00	0.00	Point (2°)	$18-18.5$	2	2.5	-	0.00025
AGASA SUGAR	7.00	0.00	Point (2°)	$18-18.5$	3	2.69	0.43	0.00025
NGC0253	88.92	-87.80	5°	$\geqslant 19.5$	0	0.01	-	0.00005
NGC3256	277.56	11.49	5°	$\geqslant 19.5$	0	0.01	-	0.00005
Centaurus A	309.43	19.44	5°	$\geqslant 19.5$	0	0.01	-	0.00005

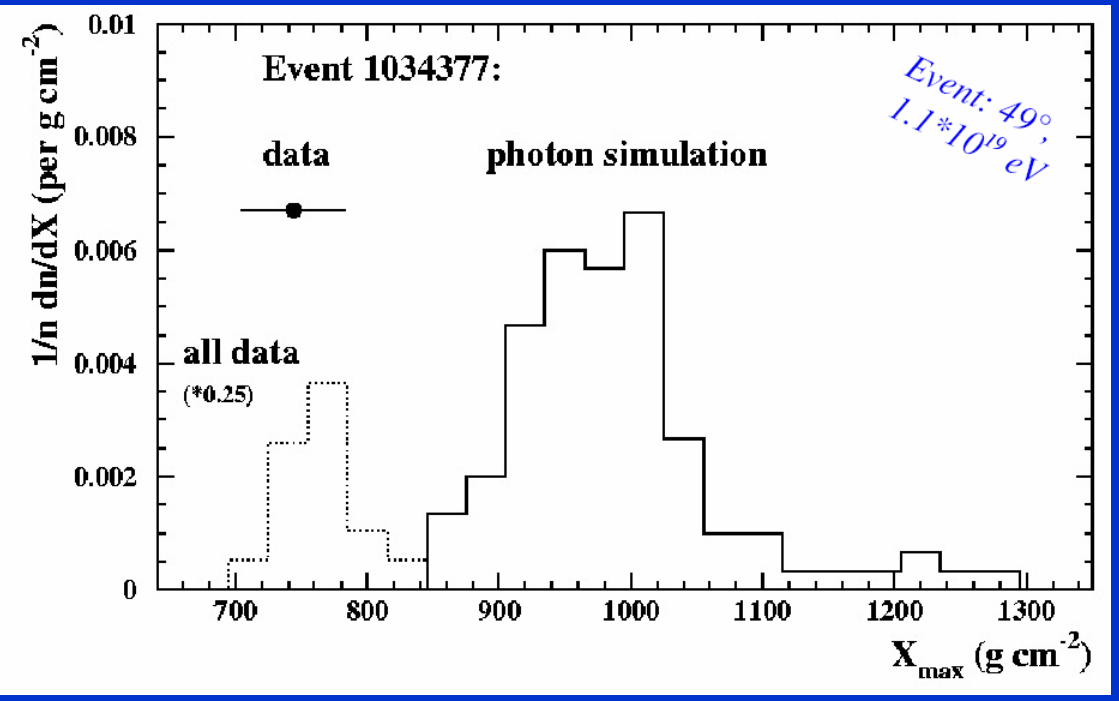
Caveats: This analysis still uses the old MC-derived energy converter.

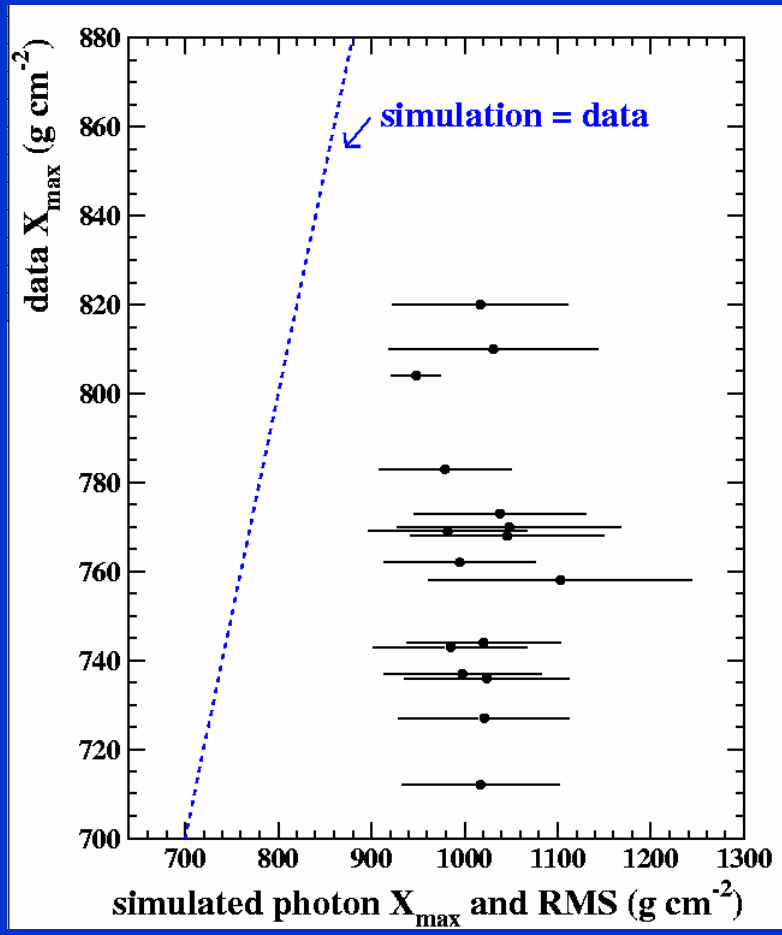
Photon Limit

- **All top-down models predict a large flux of photon primaries at some energy scale**



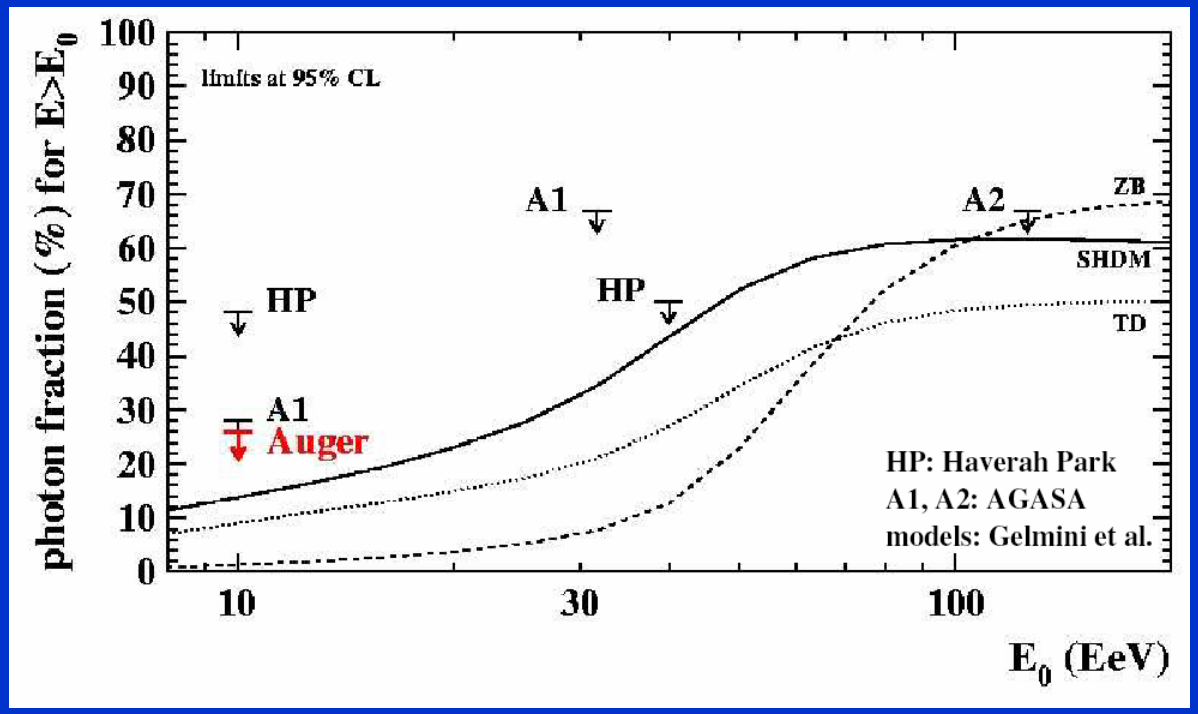
For each of 16 selected hybrid events (tracklength>450g/cm2), simulate 100 photon showers





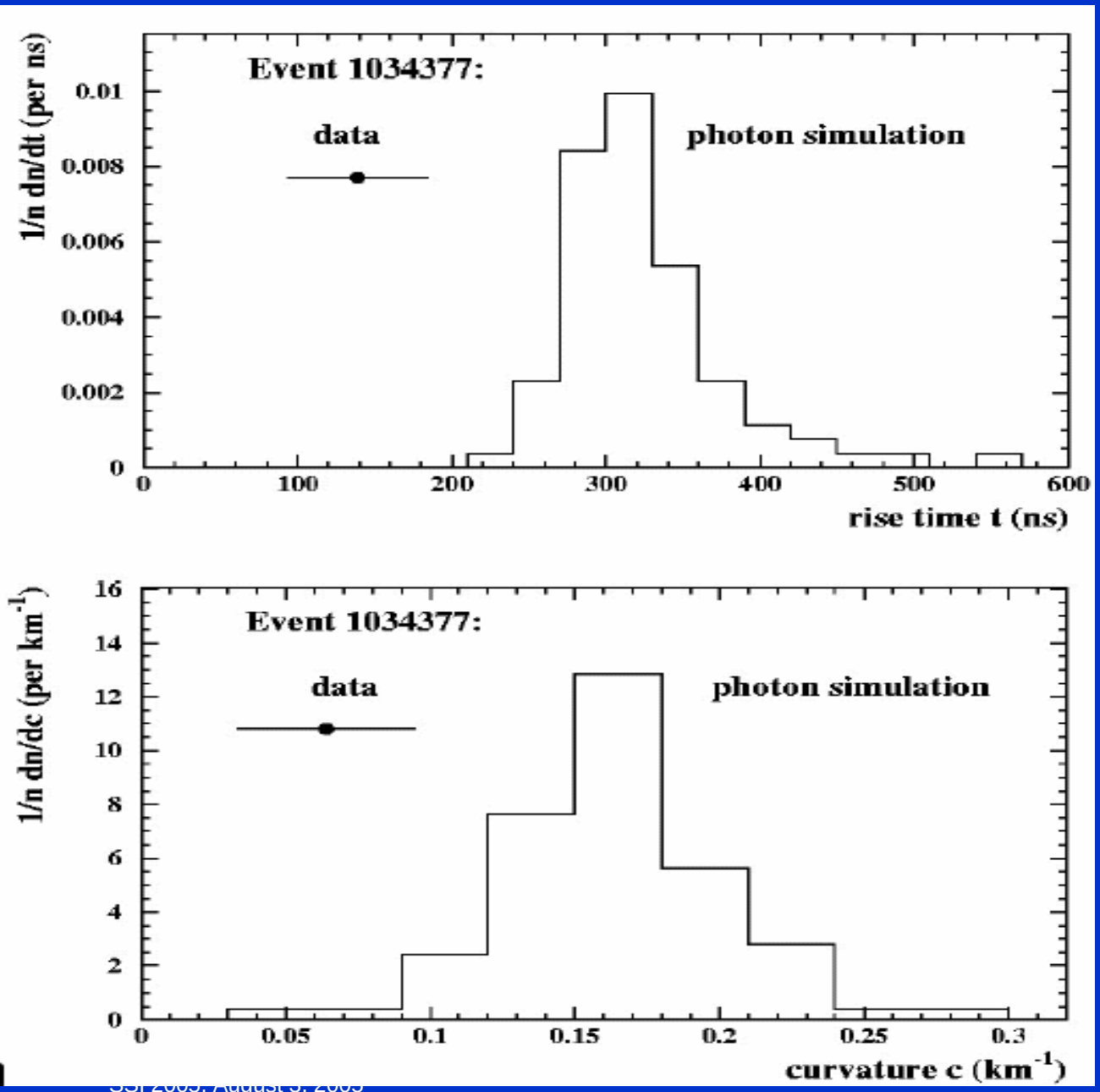
- **Sample the distributions to compute the limit such that in 95% of mock experiments, a better limit is set.**

Photon Fraction Limit Result



- **Photon Fraction <26% at 95%CL for the integrated flux of cosmic rays with E > 10 EeV.**
- **Technique is applicable for low statistics datasets at high E.**

Composition Sensitive SD observables



Risetime→ Muon flux

Curvature→Xmax

Summary

- **With only 25% of a full Auger-year exposure, we have already:**
  - **Defined our empirical spectrum analysis strategy and produced our first model-independent spectrum**
  - **Performed first studies of anisotropies in the sky**
  - **Defined a procedure for setting photon fraction limits with low statistics.**

Future Plans

- **Complete Auger South by mid 2006 (funding dependent)**
  - **Full aperture > 7000 km2 sr**
- **Fully understand our instruments.**
- **Use rapidly expanding data set (x7 in two years) to enable**
  - **Improved energy assignment**
    - ***Improve LDF measurements → Reduce systematic errors in reconstructing events***
    - ***Energy dependent CIC functions***
    - ***Reduce error from extrapolating converter to high energies***
  - **High statistics study of the trans-GZK spectrum**
  - **Anisotropy studies and point source searches.**
  - **Primary composition and hadronic interaction studies**
- **Exploit events beyond a zenith angle of 60º**
  - **search for neutrinos and exotics**
- **Begin work on Auger North**